

PETROLOGY AND DIAMONDS

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ABSTRACT

Petrology and the necessary genetic terminology, or meaningful pigeon-holing 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 that form 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 commonly encountered during diamond exploration. These rocks seem 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 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 (*AGI Glossary of Geology*). Coal, however, is another type of carbonaceous material and has many valuable uses, usually more basic than those of diamonds. Similarly, petrology has many important uses in the geological aspects of the diamond industry.

Petrology, as defined in the *AGI Glossary of Geology*, deals with the origin, occurrence, structure, and history of rocks. Diamonds occur in a variety of natural rocks: sedimentary, metamorphic, and igneous (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, being easier to find because they have larger areal extents than kimberlite or lamproite pipes, have been known for more than 2000 years. These secondary deposits include both unconsolidated and consolidated sediments. 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, and Helmstaedt 1994). Kirkley *et al.* (1991) concluded that, as a generalization,

most diamonds formed between 900 and 3300 Ma at depths >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 the destruction of the Wyoming sub-cratonic keel that stored the diamonds after the emplacement at surface of some diamond-bearing kimberlites which were derived from, or passed through, that keel (Eggler *et al.* 1988; Eggler and Furlong 1991). All of these conclusions have a considerable influence on the important area-selection procedures used in 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 those by 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) or "merely" 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 seem 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).

PETROLOGICAL INVESTIGATIONS

Kimberlites, lamproites, and similar rock types are complex, commonly 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 all outcrop and drillcore. If a suite of bodies is 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 commonly change. Mitchell 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 commonly 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, and so on. In complex bodies any one sample is unlikely to contain all of 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 an inclination to sample the harder and/or apparently fresher rocks and ignore the more altered material, but the latter may be different and may be more significant. For example, in investigations of lamproites the magmatic material is examined, whereas the associated pyroclastics are commonly ignored even though they are usually economically and texturally more important.

Further examination of these samples must include the macroscopic examination of a polished slab in addition to 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 commonly dependent on this classification.

The problems already discussed are made even more onerous as kimberlites and similar rock types are typically strongly altered. The present mineralogy (commonly, no primary minerals remain) and geochemistry can be of little value. Although not an easy task, with experience the petrography of altered rocks is potentially a 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 generally preferentially replace particular primary minerals; thus, remnant textures can be observed. These problems may be less extreme in Canada than for rocks from other more deeply weathered areas such as tropical Africa.

In these types of investigations, sample preservation and preparation may be critical. Kimberlites, lamproites, and similar rocks commonly have a wide range of grain sizes and are altered both by deuteric and by surface processes. Thus, special handling is commonly required. For example, the nature of the critically important fine-grained 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 pigeon-holing 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). An early 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 succeeding in subdividing kimberlites rather than significantly improving on its definition (Skinner 1989; Skinner *et al.* 1994; Mitchell 1993). Group-2 kimberlites have been shown to have originated from different parental magmas than Group-1 kimberlites (Smith 1983; Tainton and Browning 1991; Mitchell 1994). Mitchell (1994) suggested 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.

The term lamproite was introduced for some unusual rocks in Spain and Wyoming (Niggli 1923), and until the late 1970s, lamproites were thought to be only academic curiosities. 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 (1985, 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 Group-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).

Groups-1 and -2 kimberlites, and lamproites, are relatively rare and form only a small part of the spectrum of intra-cratonic 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, kamaugites, leucitites, and even carbonatites. So far, 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 have 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 is 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, andesite, 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 commonly 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 because the compositions give further indications about the nature of the parental magmas and, therefore, the rock type. Kimberlites, and more recently lamproites, were challenging 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.* 1994) 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 make up part of the diagnostic mineral assemblage. The definitions can 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 common presence of phlogopite (macrocrysts, phenocrysts, and groundmass), common xenocrysts and phenocrysts of olivine, together with groundmass diopside and some spinel. Lamproites are characterized by titaniferous phlogopite, leucite, glass, clinopyroxene, K-Ti richterite, olivine, sanidine, perovskite, priderite, and wadeite.

Other rock types are less well-understood, and there has yet to be some meaningful rationalization of the existing confusing historic terminology among lamprophyric and alkaline rocks. The plethora of terms for these rock types has resulted from (1) the great petrographic diversity of rocks within a clan (clan is defined by Mitchell 1994 as a suite of comagmatic rocks that has 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, at least for one clan. 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 account for the full spectrum of rocks. These features lead to a great deal of confusion. The range of rocks belonging to the lamproite clan has now been recognized, and the old rock names are replaced by a mineralogical subdivision 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 confusing, more practical, and accounts for most of the possible petrographic variations.

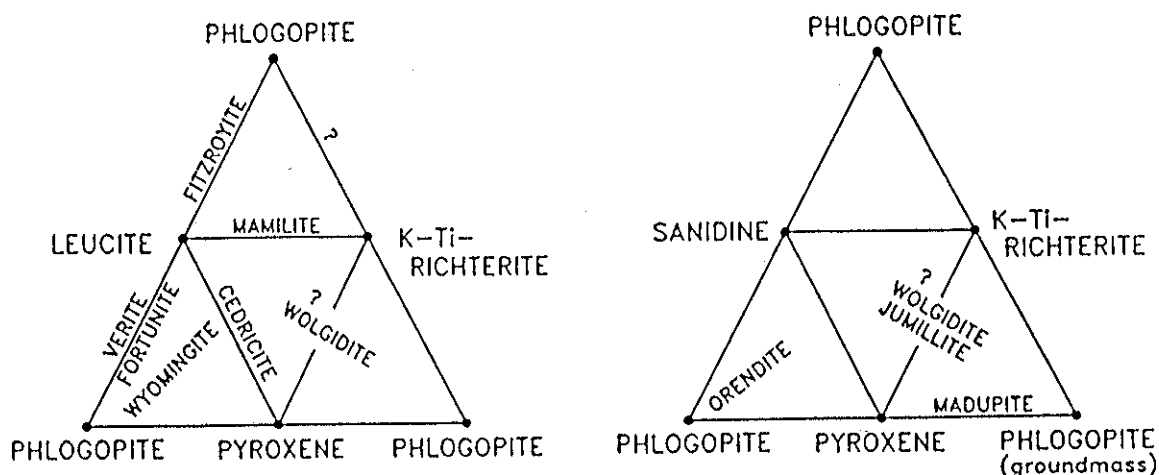


FIG. 1. Historic nomenclature of lamproitic rocks (from Mitchell 1985).

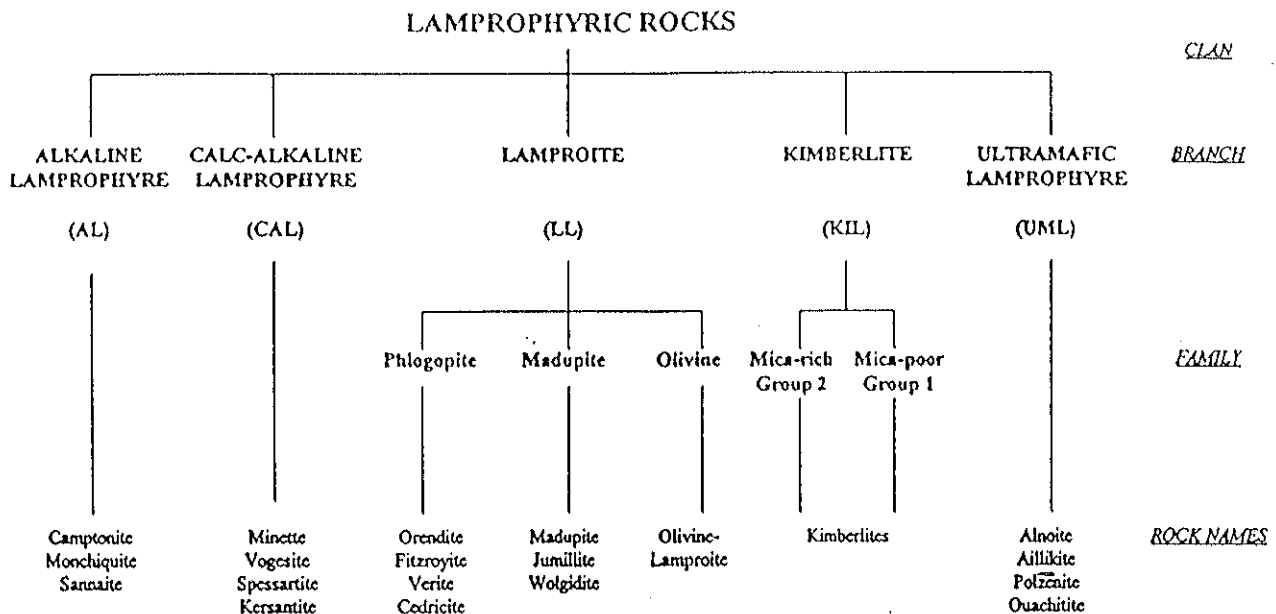


FIG. 2. The so-called lamprophyre "clan" (after Rock 1989, 1991). It should be noted that in this work it is considered that the branches of this so-called *clan* do not have any petrogenetic relationships and that this Figure does not represent a hierarchical classification scheme. Most of these rocks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

Rock (1989) suggested that lamprophyres form a *clan* of rocks that have certain common characteristics (Fig. 2). This approach implies a petrogenetic relationship between the different branches (Fig. 2). This *clan* included kimberlites and lamproites. There is no evidence to support any petrogenetic relationships between the different groups within Rock's proposed lamprophyre *clan* (Mitchell 1994; Woolley *et al.* 1994). Rock (1991) himself concluded that there are distinct magma types within his clan, and that they have varied associations and therefore different petrogeneses (Fig. 3). Mitchell (1994) has suggested an excellent rationalization of this problem by the 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. Rocks belonging to the lamprophyre-facies need not have common petrogenetic processes. Hybridization and crystallization in magma chambers account for the petrological complexities of lamprophyres (Mitchell 1994). Some of the mineralogical criteria that apply to the lamprophyre-facies are: phenocrysts of mica and/or amphibole with less clinopyroxene \pm 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 for more details). Interestingly, Mitchell does not include olivine in the definition, as it is neither ubiquitous nor diagnostic of lamprophyres. Rock (1991) described the characteristics of different groups among the lamprophyres to allow further classification of unknown rocks.

Further rationalization, however, is still required within this terminology. Commonly, therefore, it is not easy to apply these terms and criteria, either 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 lie outside of these rock types, it may be difficult, or even impossible, to meaningfully apply a rock term to them. For example, as Mitchell (1994) noted, 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 terminology 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)

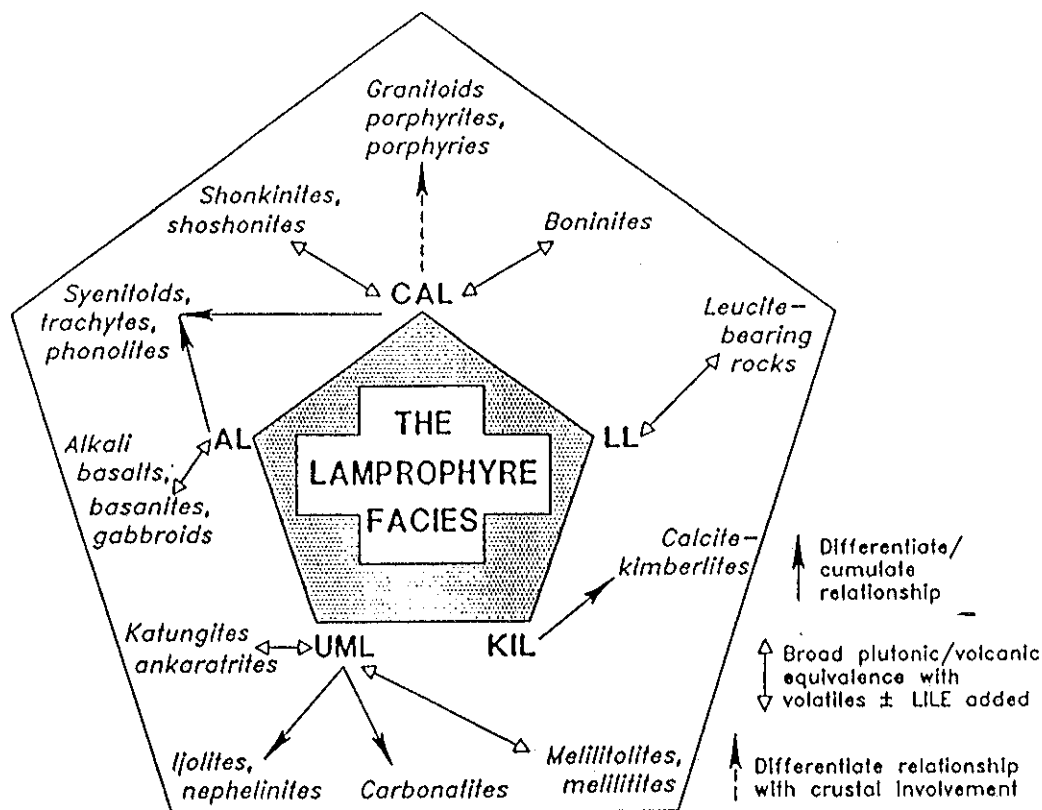


FIG. 3. Petrogenetic relationships between lamprophyres and some other igneous rock types (after Rock 1989, 1991). Rock's term 'clan' has been replaced here by facies.

of the De Beers Consolidated Mines Ltd. Geology Department (unpublished data). This term has been introduced into the literature by Mitchell. This term is devoid of petrographic connotations, so Mitchell supports its use as an interim name until petrologists can agree on a stem name that conveys the nature of the parental magmas involved. The term encompasses 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 becomes melilitite diopside phlogopite melnoite, and aillikite becomes a phlogopite calcite melnoite, and so on (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 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. The potentially diamondiferous rock types, Groups-1 and -2 kimberlites and olivine lamproites, are clearly shown and are separated from the other rock types in Figure 2. 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 encountered during diamond-exploration programs (Fig. 4). Most rocks within one clan will display characteristic features which are used in the definition of that rock type (Fig. 4). The range 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

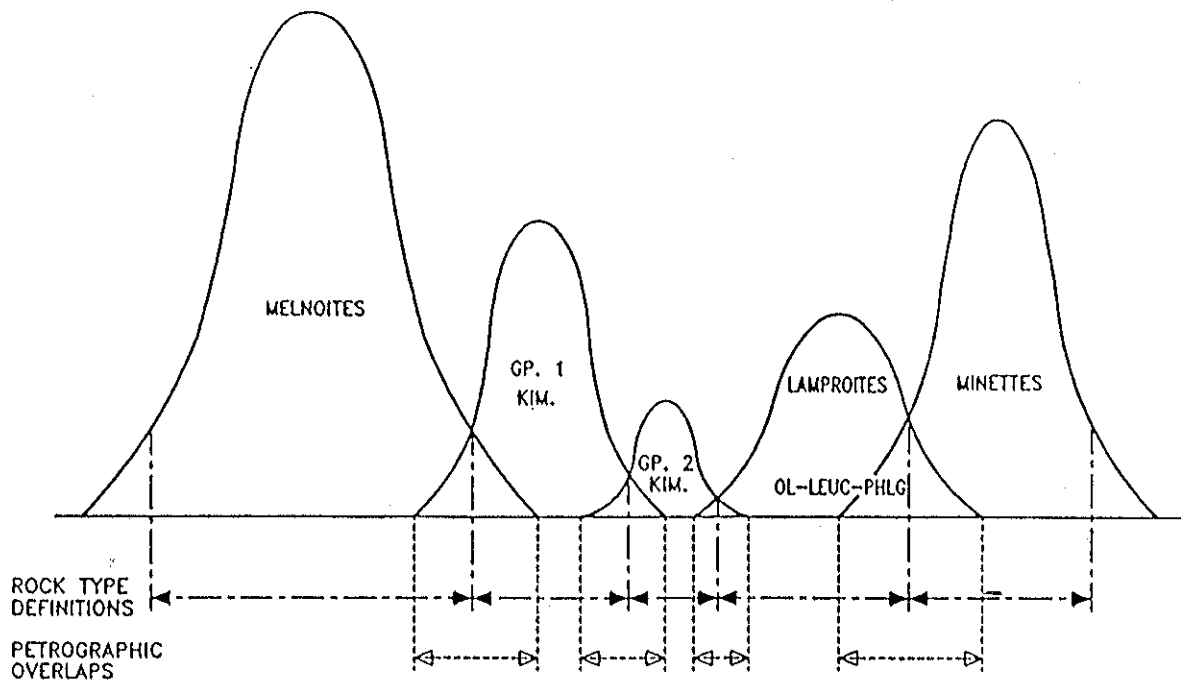


FIG. 4. Petrographic ranges for the rock types most commonly encountered during diamond exploration. The horizontal axis schematically represents the petrographic variation within each rock type. The heights of the curves indicate the relative worldwide abundances of each rock type (not to scale). The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

4, melnoites are the most common and display the widest petrographic variation, whereas 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 commonly difficult, and may not be 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 because these rocks have had time to crystallize to a coarser groundmass than that in extrusive rocks. The nature of the minerals in hypabyssal rocks is then a direct reflection of the parental magma or the clan from which they are 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, and in press), Mitchell and Bergman (1991), Rock (1991), and Woolley *et al.* (1994) discuss the criteria and present guidelines for the recognition of kimberlites, lamproites, and other rock types, so this aspect will not be discussed further. Obtaining the compositions of the primary minerals in these rocks can commonly be extremely helpful, and may be essential. Mica compositions have been shown to be particularly useful in distinguishing the overlapping rock types shown in Figure 4, e.g., distinguishing Group-1 and -2 kimberlites from each other and from olivine lamproites, or phlogopite lamproites from minettes (Scott Smith and Skinner 1984a; Mitchell and Bergman 1991). 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 seems to be a much-used tool in diamond exploration, but it has not proved to be particularly successful in discriminating different rock types. As noted by Mitchell (in press), 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 its primary minerals, 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) has provided further discussion on this topic. Elphick *et al.* (1993) discussed the unreliability of whole-rock geochemistry in their investigations of the James Bay Lowlands olivine melilitites. They concluded that such results can be misleading "without intensive petrographic research".

SUBDIVISIONS 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 subdivisions 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 1984 a,b; Mitchell 1986, 1994). These mineralogical classifications are best applied to hypabyssal or non-glassy magmatic rocks, and are based on the modal proportions of the primary minerals. Most of these minerals crystallized from the magma, and they, therefore, directly reflect its nature. This type of classification is therefore useful in defining different batches of magma which have reached the surface, and thus 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 is described as a phlogopite monticellite kimberlite, for example, if 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, commonly 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 volcanoclastic rocks, are rapidly quenched and therefore have not had the opportunity to crystallize the late-stage minerals which are usually the main basis for the mineralogical classification.

Modal analyses are an extremely useful petrographic tool. However, there seems to be a reluctance to determine and use such analyses; thus, the application of mineralogical classifications is, unfortunately, commonly based on visual estimates. Modal analyses are an excellent way of presenting petrographic data. Examination of a modal analysis provides a reader with a quick and fairly accurate indication of a rock. Many of the pertinent features in published petrographic descriptions are commonly hidden, not included, or even overlooked.

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 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 (Mitchell 1994). 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 re-worked. Rocks resulting from reworking are best termed resedimented volcanoclastics (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 commonly 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.

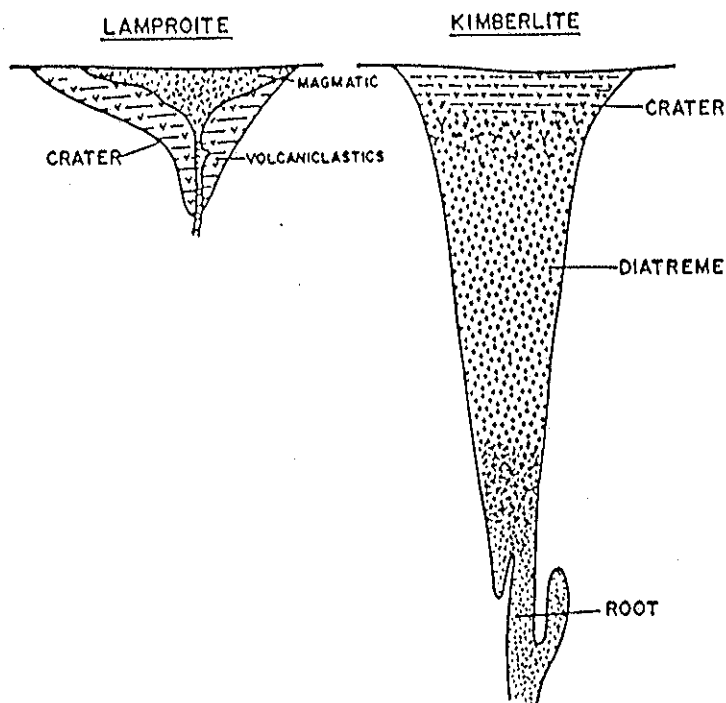


FIG. 5. A comparison of schematic geological models of lamproite and kimberlite pipes (modified after Scott Smith and Skinner 1984a). Not to scale.

Different clans of rocks originate from different parental magmas. These magmas not only have different compositions which are reflected in their mineralogy, but they also have different properties that affect their emplacement processes and, consequently, their textural classifications and pipe models (Fig. 5). Lamproite pipes typically consist of craters infilled with primary ash and lapilli tuffs, and effusive magmatic rocks. Standard volcanological terminology can be applied to these and to some other related rocks, such as minettes. Many kimberlites have styles of emplacement (Clement 1982) different from standard volcanic processes described in the literature (e.g., Fisher and Schmincke 1984; Cas and Wright 1987). The main reason for these differences seems to be the abundant carbon dioxide that is still incorporated within many kimberlite magmas when they approach the 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).

Kimberlites differ from many volcanic rocks in that extrusive magmatic or effusive equivalents have not yet 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 downwards 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. Investigation of the material occurring within many kimberlite craters has been hampered because most of the better investigated examples have been extensively altered. For others there is little published information. These craters can be infilled with both primary and resedimented volcanoclastic kimberlite. The latter may include crater-lake sediments, such as found at the Orapa mine in Botswana. Kimberlite craters 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 seem 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 in which 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 Dept., which has 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, b; Clement and Skinner 1985; Clement and Reid 1989; Skinner 1989). Scott Smith (1992) discussed 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.

Although Groups-1 and -2 kimberlites and lamproites, as well as some secondary deposits, can all form successful diamond 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 or more difficult to find than kimberlites. Most of the world's diamonds currently are derived from kimberlite mines; thus, 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 Archean Slave craton in the NWT seem to be a good example of the application of Clifford's Rule (Janse 1991, 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 off 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 may require different interpretations (e.g., Atkinson 1989; GSC Open File 1989; Fipke and Nassichuk 1991; Muggeridge 1991; Scott Smith 1992). Similar comments can be made for Group-2 kimberlites (Skinner 1989; Tainton and Browning 1991; Skinner *et al.* 1994; Mitchell in prep.).

Group-2 kimberlites thus far are 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 Group-2 kimberlites and lamproites, but not of Group-1 kimberlites (e.g., Mitchell and Bergman 1991). 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 were either derived from, or were

contaminated by, such variably 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 unique characteristics. 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 instead may 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 bodies are discovered during an exploration program, petrological classification becomes important. From a diamond-exploration viewpoint, it is firstly important to establish the relevant clans and then 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. So far, these rock

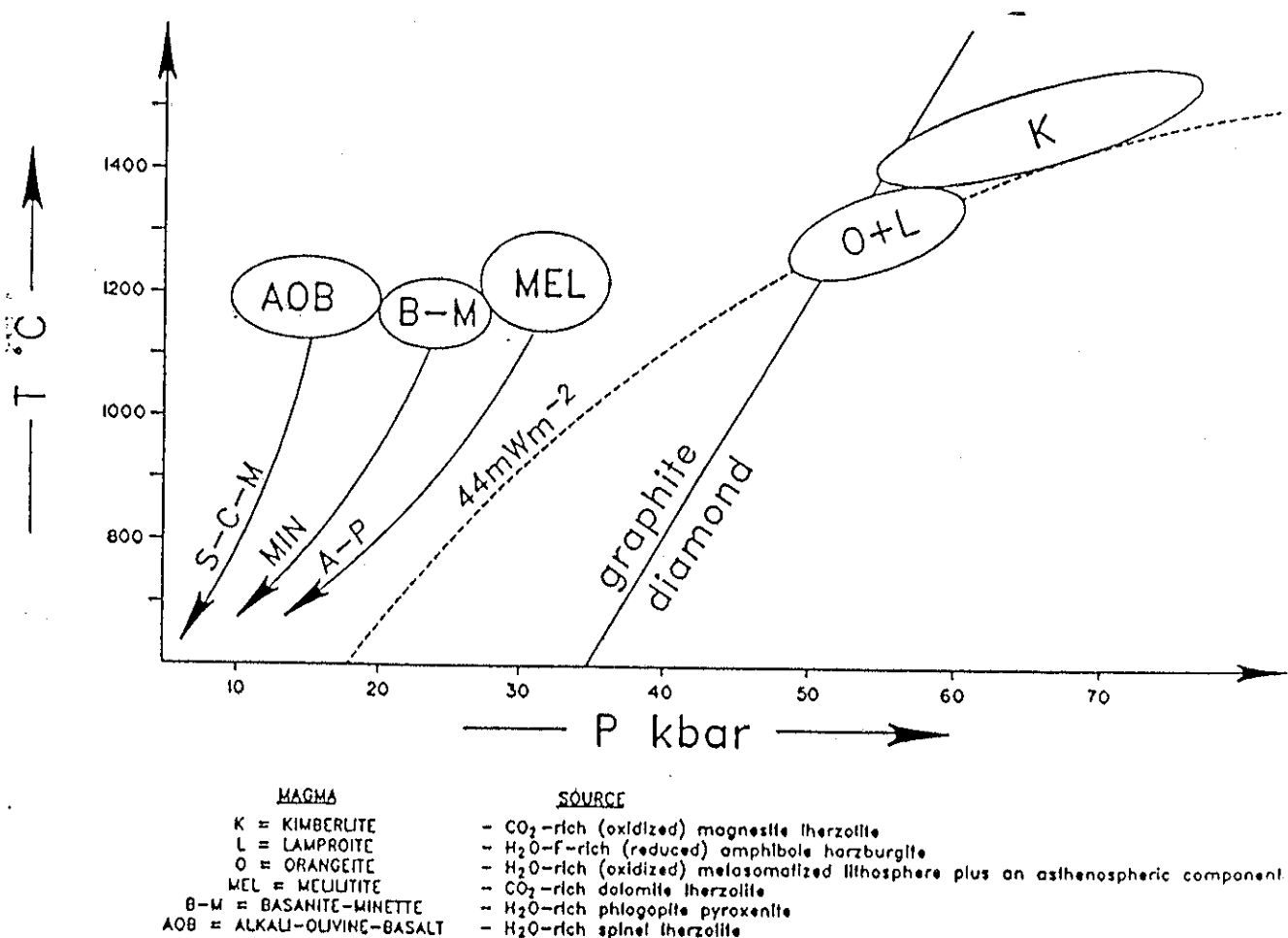


FIG. 6. Source regions, pressures, and temperatures of formation of some mantle-derived magmas relative to a representative continental geotherm and the diamond-graphite transition (after Mitchell 1994). All magmas are capable of crystallizing rocks of lamprophyric aspect under appropriate conditions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

types seem to include only Groups-1 and -2 kimberlites (orangeites) and lamproites (Fig. 6). These rock types must be recognized to prevent further follow-up work on other rocks that have little economic potential. Rocks which have originated from outside the diamond stability field obviously have no potential to carry diamonds; examples are the minettes and melilitites shown in Figure 6. Other associations are illustrated in Figure 3. Examples in Canada for which the better application of such classifications could perhaps have prevented further exploration work include the alnoites or olivine melilitites and tuff breccias in the Hudson Bay Lowlands (Janse *et al.* 1989), the breccia pipes associated with the vast minette province in the area of Dubawnt Lake, NWT (Peterson 1993, 1994; Petersen *et al.* 1993; Pell and Atkinson 1993), the Ile Bizard alnoite intrusion, which forms part of the Monteregian igneous province in Quebec (Raeside and Helmstaedt 1982; Mitchell 1979, 1983), 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, whereas Dubawnt Lake is an example of the overlap between phlogopite lamproites and minettes (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,b; MacFadyen 1993) and the Fort a la Corne kimberlites in Saskatchewan (Lehnert-Thiel *et al.* 1992). These examples are additional to the recent discoveries in NWT.

The potential for new rock types carrying significant quantities of diamonds must always be considered. Other authors have noted that lamproites and lamprophyres were relegated to the status of non-prospective rocks prior to the discovery of the Ellendale bodies in Western Australia (*e.g.*, Helmstaedt 1994). It must, however, be re-emphasized 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. In this respect, it is also pertinent to note that all of the newly discovered and recognized diamondiferous olivine lamproites were initially 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. Terming them kimberlites obviously 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 forty years after the leucite lamproites were relatively well-known. Among the other rock types which show greater similarities to kimberlites, the most likely candidates for carrying reasonable quantities of diamonds seem to fall among 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), which in turn suggests 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 has been discovered. For example, the application of mineralogical classifications among the wide variety of rocks in the lamproite clan has shown that significant quantities of diamonds occur only in olivine lamproites. No lamproites (ss) 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, and all of the diamondiferous rocks are olivine lamproites (Scott Smith and Skinner 1984b). The Prairie Creek lamproite is also a good example of the application of subdivisions based on textural classifications. In lamproites, economic diamond grades so far seem to be confined to crater-facies volcanoclastic material. At Prairie Creek, most of the diamonds are recovered from the olivine lamproite lapilli tuffs (so-called "breccias"), and the magmatic olivine lamproite yields only a small quantity of diamonds. The olivine lamproite lapilli tuffs were mined during the earlier part of this century, and are 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 subdivisions, 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) showed that the magmatic olivine lamproite at Prairie Creek has a magnetic response, whereas 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 are 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 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, 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 NWT and Saskatchewan. A spectrum of ages, however, should be expected within the Slave craton. In the NWT, 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 suggests 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. Examples of decreasing size with increasing age, as a consequence of different degrees of erosion, are poor in Canada because kimberlites of different ages 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). The Devonian-age Cross kimberlite in B.C. 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,b).

Deviations from established pipe models (Fig. 5) should be expected. The Fort a la Corne kimberlites seem to be such an example. Diatremes apparently have not been developed in these bodies (Scott Smith *et al.* 1994), thus reducing the potential ore reserves of any one body. Some similarities between some of the kimberlites on Somerset Island and the Fort a la Corne bodies (Scott Smith *et al.* 1994) deserve further attention.

Crater-facies rocks are complex, and each volcanic centre 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). Some comments on the diamond distributions in the different facies of kimberlites and lamproites are given by Scott Smith (1992) and Mitchell (1991). Detailed published information of contrasting grades in different facies within a kimberlite pipe in Canada are not yet available. The kimberlite processing undertaken by Kennecott Canada Ltd. on the DO-27 pipe in the NWT, 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 (*George Cross Newsletter* No. 150, August 8th, 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.

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About the author:

Barbara H. Scott-Smith graduated in 1972 with a B.Sc. (Hons.) and then a Ph.D. in Geology from Edinburgh University in 1977, following which she worked as a Research Mineralogist for Anglo American Research Laboratories in Johannesburg, South Africa for five years. In 1982 she emigrated to Canada, where she works as a private consultant. Her activities have included investigations into the petrology of kimberlites and similar rock types, with an emphasis on petrography in relation to world-wide diamond-exploration programs and mining ventures. Her project experience includes Canada, USA, Greenland, Australia, South Africa, Lesotho, Zambia, Ivory Coast, Botswana, China, India, Europe, Brazil, and Russia. She is a registered Professional Geologist in B.C., a member of CIM and other professional societies, and is a member of the IUGS sub-commission for the nomenclature of kimberlite and related rocks.

PROCEEDINGS

OF

DISTRICT 6 CIM

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OCTOBER 11 - 15, 1994
VANCOUVER, BRITISH COLUMBIA

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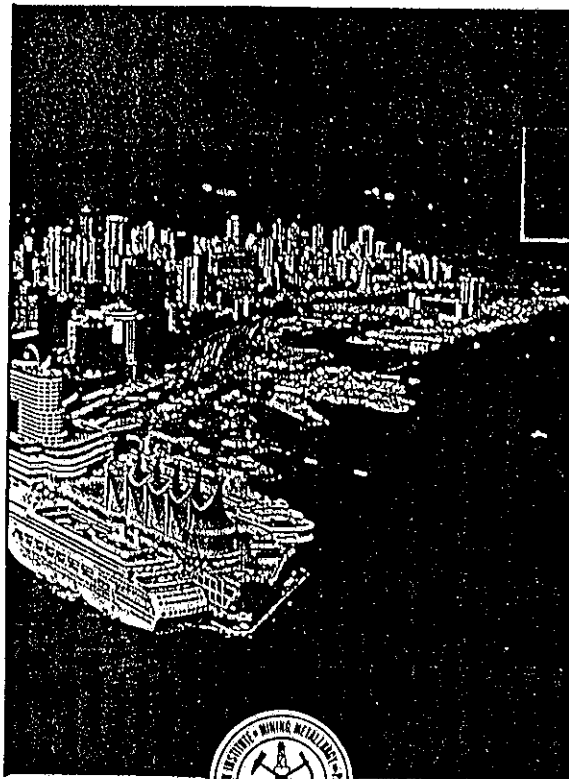
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Paper No. 33 — 9:45

Petrology and Diamonds

B.H. SCOTT-SMITH, Scott-Smith Petrology

Petrology and 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. Kimberlites and lamproites, the only known primary sources of economic quantities of diamond, have been shown to be petrogenetically distinct rock types. Although these magmas only act as a transporting agent for diamond, the differences between these, and other, rock types have important implications for diamond exploration programs. Correctly classifying and interpreting the geology of such rocks, however, is not a straightforward task. Lamproites are rare and have yet to be discovered in Canada. The textural and mineralogical classification and the near surface emplacement of kimberlites are important factors in exploration and evaluation which can now be illustrated using examples from the rapidly rising number of known kimberlites in Canada.



*The Sixteenth
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**The Future
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Domestic and
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October 11-15, 1994

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