A REVIEW OF DIAMOND EXPLORATION PHILOSOPHY, PRACTICE, PROBLEMS AND PROMISES

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INTRODUCTION

Since inception in the post-war period the introduction of well-funded, scientifically based surveys of large areas for diamond has more than doubled the global supply of natural stones to the market. Pre-war production is mainly attributed to the historical and "prospector" period, albeit often very skilled and systematic, but lacking the funding and technology to advance the search for resources into geologically favourable areas that were relatively inaccessible by virtue of isolation, climate or surficial cover, and which required scientifically based concepts for area selection and an improved technological approach to explore them.

Significant modern discoveries have been primary deposits, pipes, generally at the expense of major new alluvial supplies reflecting:

(i) recognition that large primary deposits can represent long-life mines, amenable to large scale mining methods, with secure consistent production warranting the exploration funding required;

(ii) that alluvials, by virtue of their nature, had been more readily discovered by direct prospector recognition of diamond, in contrast to the indirect and more difficult exploratory methods required for pipes.

This major increase in exploration-initiated pipe production has, most significantly, been marked by the development of new production centres. These are away from countries where the major fields were initially alluvial producers, discovered in past centuries or early in the 20th, and where pipe discoveries generally followed as a result of follow-up of alluvial/elluvial dispersion trains. In contrast the most marked effect of modern exploration has been the rapid rise of countries that hitherto were nil or insignificant producers of diamond but are now major producers, notably of course the USSR and Botswana and latterly Australia.

In respect of the last the selection of the present venue of the 4th IKC is endorsement of very recent exploration that:

- has extended the occurrence of large economic pipe mines to a third continent;
- will increase production of natural diamond by 40 to 50 percent this year;
- has confirmed lamproite as an alternative primary source to kimberlite for economic concentrations of diamond;
- increased the world's portfolio by some 150 additional kimberlite, lamproite and related rock occurrences of all sizes that are available for study both by academia to further our understanding of the mantle, and also by the exploration industry for the ongoing advancement of exploration techniques.

The rapidity with which increased production from new countries has been achieved by modern exploration, an occurrence not restricted to diamonds, raises of course the inherent question of where will it end if exploration continues at its post-war rate - a "problem" or a "promise", for which the answer can only lie with expanding markets, elimination of uneconomic producers, or a combination of this and controlled supply to the market place.

THE EXPLORATION PROCESS

Exploration for diamonds is an industry, or national response to demand for more of a particular product than existing mines can supply at an economic price. It comprises "risk" that unsuccessful exploration will result in a loss of money or other resources, and "reward", i.e. an economic mine producing profit, or alternatively, a product that a nation, for example, cannot afford to import, or for security purposes, requires to be produced internally. There are other commercial constraints, in a free enterprise economy; access to land, secure title to discoveries, and realistic rules for commercial development and mining must be in place.

The exploration process comprises therefore:-

(i) commercial factors
- need and market
- access to land and commercially acceptable rules for exploration and exploitation;
- adequate risk funding

(ii) technical factors
- area selection - development of advanced concepts for emplacement and preservation of economic sized pipes and grades (value) so that practical areas of prospective ground, giving the greatest probability for economic discovery, are selected. Area selection techniques need major improvement.
- search technology - it is increasingly recognised that major exploratory successes are achieved by indirect exploration for large primary sources in areas where prospector discovery was precluded by other factors, e.g. lack of exposed alluvials, surficial overburden, isolation, climate, etc. This has required adaption of existing techniques, remote sensing, indicator sampling, direct diamond detection, geophysics, etc. to progressively varying geological, geomorphological, climatic and other regimes. This is an ongoing process with vast scope for improvements of existing practices and developments of new technology.

(iii) human factors
- the right people, trained, field orientated, observant, inquisitive and motivated.
- risk tolerant management committed to success.

Area Selection

The empirical study by Clifford (1967) showed that diamondiferous kimberlites are restricted to areas cratonised by 1500 My. Suggested association of West African kimberlites with the passage of the continent over hot spots has drawn attention to the alignment of kimberlite and the use of linears during exploration area selection. Diamondiferous lamproites are associated with rift zones (Luangwa Valley, Zambia; Prairie Creek, Arkansas; Ellendale, Western Australia) and transcurrent faulting developed along Proterozoic mobile zones (Ellendale and Argyle, Western Australia). These Western Australian mobile zones were stabilised by 1800 My, hence Clifford's view also applies to lamproites and is still useful in area selection.

Establishment of the prospective age of kimberlite helps target exploration areas both for alluvials and primary sources, e.g. the discovery of the Triassic Dokolwayo pipe intruding an inlier of basement granite surrounded by overlying Upper Karroo sediments (Hawthorne et al, 1979). In this case diamonds and indicators in the Karroo sediments provided the lead towards location of the pipe.

The geomorphological environment determines the degree of preservation of the kimberlites (Gold, 1984), uplifted areas being subjected to erosion and rapid removal of the upper levels of the diatremes. Good stream drainage may be present in such uplifted areas, and stream sampling for kimberlite indicator minerals may be an effective search technique, but if the kimberlites preserved have been eroded down to stringers or thin dykes they are of relatively low commercial value (eg. North Kimberley, Western Australia; Sierra Leone). Adjacent low lying ground is subject to deposition rather than erosion. There is a better chance of preservation of the upper levels of diatremes (e.g. West Kimberley lamproites), but they may be buried by overlying sediments. Stream drainage on plains country may be poor and indicator mineral searches may have to be carried out by the grid loaming technique.

The nature of alluvial diamond deposits is related not only to areas of deposition and manner of concentration, but also to climate. Rapid stream deposition under an arid climate may result in little concentration, with grades tailing off rapidly downstream (e.g. Argyle). In contrast, tropical humid climates with attendant chemical weathering cause breakdown of the less resistant components in the alluvials, with consequent upgrading of the diamond content (Hall et al, 1985; Thomas et al, 1985). Such alluvials may produce ore deposits further from their primary diamond source (eg. Tertiary alluvial terraces in South Africa). Where concentration factors are extreme, such as on the marine beaches of Namibia (Hallam, 1964) payable alluvials may be found at extreme distances from source. A further effect of transportation is improvement in the quality of the stones preserved, the more fractured and easily broken stones being eliminated. On the other hand average diamond sizes decrease downstream (Sutherland, 1985), though local sorting effects can cause reversals in the trend.

Search Technology

Prospectors traditionally fossicked in river gravels for diamonds, and from this approach has stemmed the indicator mineral search techniques using kimberlite minerals as pathfinders.

The chemistry of minerals from kimberlite and lamproite, from mantle nodules within these rocks and from diamond inclusions, has been characterised by extensive analysis (eg. Dawson and Stephens, 1977; Sobolev, 1977). This characterisation not only enables chemical comfirmation that suspected indicator minerals obtained in a field sampling programme have indeed emanated from a kimberlite, but also allows estimation of the diamond potential of the kimberlite source. Hence newly found clusters of kimberlite can be ranked in order of priority for evaluation of diamond content by bulk sampling (Gurney, 1984; Sobolev et al, 1984).

Field methods of processing samples involve gravity separation of the heavy minerals by gold pan or jig, and visual observation of the concentrate to identify the kimberlite indicator minerals. Such practice is effective where the minerals are coarse grained (+1mm) and numerous, but where success may be represented by recovery and recognition of 1 single indicator mineral grain of, say, 0.4mm size in a whole sample, greater efficiency of laboratory processing is a requisite.

Where river drainage exists, indicator minerals from kimberlite are released by weathering and move by soil creep or sheet wash into the nearby streams. Downstream transportation of these minerals provides a train leading back to the kimberlite. In Yakutia, USSR, the cold climate inhibits chemical weathering and olivine grains -1.0 + 0.5mm travel up to 100 km from kimberlites without significant wear (Afanasev et al, 1984). In Africa and Australia, in warmer climates with marked seasonal rainfall, indicator minerals have been found to travel from 20 km or more for 0.4mm size grains to only 1 or 2 km for 1.0mm size grains dependant on stream gradient and stream flux (Bardet, 1973; Mosig, 1980). As the indicators are heavy they concentrate en route in natural trap sites, eg. above rock bars, in crevices in bedrock, in gravel point bars often on the inside of meanders. In exploration small samples of this gravel, typically 8 - 40 kg in size, are collected at reconnaissance intervals of 3 to 15 km along the streams, a typical coverage of say, 1 sample per 50 sq km (Atkinson et al, 1984). Where kimberlite indicators are found then follow up gravel sampling is undertaken at closer intervals until the source area is defined. This technique has been responsible for the discovery of the economic Mir and Udachnya kimberlite pipes in USSR, and the Ellendale and Arygle lamproite pipes in Western Australia. In north America, gravels from eskers have been sampled in similar manner.

In regions which lack effective drainage the loam sampling technique is used and consists of collecting the top 1cm of soil in which wind deflation has concentrated the heavy minerals. Initial reconnaissance work may be widely spaced, eg. 13.5 kg samples on a 1.6 km square grid as described by Bardet (1973) for exploration in Tanzania. Follow up work requires more detailed sampling to locate individual pipes, often characterized by anomalous haloes of indicators spread over some six times the area of the pipe.

Bulk sampling of one to several cubic metres of gravel or rock is required if diamonds are sought directly during prospecting operations. This method is normally used in the search for alluvial deposits (eg in west Africa, Bardet 1973), particularly those far from source. The method can also give information on the presence of diamonds in a stream catchment where indicator minerals are already known, and hence provide encouragement to continue searching for the primary kimberlite host. The disadvantage of the method is the high cost of bulk sampling, and the attendant need for concentrating machinery (unless an abundant supply of cheap labour is at hand) which restricts prospecting mobility. The method is not readily applicable to arid areas and to regions without stream drainage.

Air photo interpretation is of wide value in diamond exploration, providing information on regional structure and geomorphology during area selection, and being used as a mapping tool in association with field work when delineating alluvials or prospecting for kimberlite. Many pipes and dykes have been located in southern and central Africa where they gave rise to vegetational features, circular depressions or mounds, or tonal differences visible on air photos (Mannard, 1968; Edwards and Howkins, 1966).

Landsat imagery pixels are too coarse to detect individual kimberlites (Nixon, 1980), but such imagery has been used in regional structural analysis of kimberlite provinces (Woodzick and McCallum, 1984). The airborne multispectral systems being developed today have much greater resolution, can detect the signature of specific clay minerals and therefore have the potential to locate kimberlite weathering products. Future developments of this method may become important in diamond prospecting.

Geophysics has been used in kimberlite exploration since the 1930s, but early use was generally confined to delineation of pipes rather than exploration for them, due to the available technology of the day. Magnetic gravimetric and resistivity contrasts between kimberlite and country rock have been employed to locate pipe boundaries and provide information on the size and depth extent of pipes. All early surveys were conducted on the ground using relatively cumbersome equipment making regional coverage very difficult and time consuming. USSR scientists were the first to use airborne magnetic surveys extensively in kimberlite exploration, many of the pipes in Yakutia being found by this method. Since the 1970s, geophysical surveys, particularly airborne methods, have focussed on kimberlite exploration rather than delineation. The greatly improved technology and understanding of airborne magnetometry and radiometric systems, plus the advent of digital recording, has made these the most popular methods. In Australia alone it is estimated that some 200,000 line km of such airborne surveys are conducted each year in diamond exploration. Airborne electrical methods such as INPUT are also effective, but it is aeromagnetics that have been responsible in the late seventies for finding most of the pipes in the West Kimberley, Australia and in central Botswana.

Kimberlites and lamproites are enriched both in elements of ultramafic affinity (eg. Mg, Co, Ni, Cr , Cu) and in "incompatible" elements (eg. LREE, Ba, Sr, Rb, P, NG) (Dawson, 1967; Smith, 1984) which gives these rocks a characteristic identification signature. This signature is used in two ways: 1. in pathfinder regional stream and soil surveys seeking to locate kimberlites suspected to occur nearby (Gregory and Tooms, 1969); 2. as support towards the identification of rocks from weathered outcrop or drill cuttings. Stream and soil geochemistry is of limited use because the detectable halo of chemical dispersion around kimberlites rarely exceeds a few tens of metres in soil, or a few hundreds of metres in streams. Chemical analysis for rock identification is cheap and effective and particularly useful where extensive oxidation and weathering of kimberlitic rocks renders their identification very difficult by optical or petrological methods in the field or laboratory.

EVALUATION OF DIAMOND DEPOSITS

Evaluation of diamond deposits requires determination of the volume of ore reserves by conventional drilling and pitting methods, plus calculation of the in-situ worth of the ground. This worth (revenue) is related to both grade (ct/t or ct/m^3) and quality of the diamonds. The relative rarity of diamond in an economic deposit, from 0.01 to 3.5 ppm (Atkinson et al, 1984), combined with the need for a parcel of at least 5000 ct for valuation (Sutherland and Dale, 1984), shows why bulk sampling operations involving treatment of several hundred to several thousand m^3 are required during evaluation work.

Diamond size distributions are lognormal in alluvial deposits (Sichel, 1972) and in lamproite and kimberlite (Hall and Smith, 1984), and special techniques based on classical statistics have been devised for grade and revenue calculations (Oosterveldt, 1972). Recent ore reserve estimations for the Argyle diamond deposits (Boxer et al, 1985) used both classical and geostatistical methods of calculation, and found good agreement between the methods.

PROBLEMS AND PROMISES

The discovery of diamond-bearing lamproites at Ellendale (Atkinson et al, 1984) and Argyle (Atkinson et al, 1985) has revealed a new primary source rock as a target for diamond exploration, and raises the query as to what other mantle-derived igneous rocks may also be diamondiferous.

Diamondiferous lamproites contain the same indicator minerals such as pyrope, chrome diopside and picroilmenite (the latter is rare in lamproite) that also characterise kimberlites, but they are not as abundant and usually finer grained. The megacryst suite of indicators (Nixon and Boyd, 1973), large picroilmenites, Ti-rich garnet and diopside, zircon, etc, appears to be absent. Other minerals such as priderite, richterite, can be used as indicators of lamproite (Atkinson et al, 1984).

Alluvial diamond localities without such indicators have traditionally been viewed as far removed from any primary source rock. Diamond, because of its hardness and inertness to chemical weathering, survives both long distance of travel and recycling through the sedimentary record. Local reconcentration may give rise to alluvial ore deposits such as the Namibian marine terraces. Elsewhere a wide geographical dispersion of occasional diamond may occur, such as those being reworked from the Roraima Series sediments in Venezuela. Indicator minerals such as garnet, chrome diopside and picroilmenite are not as resistant to chemical weathering and abrasion, especially under tropical climates. Hence the presence of indicators within the sedimentary column suggests a local source, though it may still be blind.

The discovery of diamond in lamproite accompanied by relatively few classical indicator minerals now shows that alluvial diamond deposits with a virtual absence of indicators such, as at Argyle, can exist close to primary source. This throws into question the distant primary source invoked for many of the world's alluvial diamond localities.

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