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GEOLOGY AND EVALUATION OF THE GUINEAN DIAMOND DEPOSITS[1]

by

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(11 figures and 5 tables)

RESUME.- Les gisements diamantifères aux teneurs économiques et les kimberlites de la Guinée se concentrent dans une région limitée par les villes de Kissidougou, Kerouane et Macenta dans le sud-est du pays. Les kimberlites diamantifères percent le craton archéen de la Dorsale guinéenne et semblent étroitement liées au morcellement de Gondwana. Le contrôle structural de la distribution de kimberlites est évident. La direction sublatitudinale s'est présentée comme la direction la plus favorable à l'emplacement des kimberlites. Les diamants se sont dispersés dans deux systèmes majeurs de drainage: le bassin Atlantique et le bassin du Niger. Les caractéristiques de déposition du gravier et des diamants sont différents dans ces deux bassins et les implications sur l'estimation des teneurs sont discutées. Les diamants présentent comme formes crystallographiques surtout l'octaèdre, le dodécaèdroide et leur macles, tandis que les cubes sont presque totalement absents.

ABSTRACT.- Kimberlites and economic diamond deposits are concentrated in an area bounded by Kissidougou, Kerouane and Macenta in Upper Guinea. The kimberlites are closely related to the break-up of Gondwana and are intruded into the Archean formations of the Guinea Rise. Kimberlite emplacement is structurally controlled with the sublatitudinal direction as the most favourable direction. All kimberlites seem diamondiferous. The diamonds are dispersed into two major drainage systems: the Atlantic and Niger drainage. Diamond and gravel deposition in these two drainage systems are different and their implications on grade estimation are discussed. The most common crystallographic diamond forms are the octatedron, the dodecahedroid and their macles, while cubes are very rare.

INTRODUCTION

Economic diamond deposits and kimberlites occur in an area bounded by the towns of Kissidougou, Kerouane and Macenta in Upper Guinea (Fig. 1). The Kimberlites are of Cretaceous age (Bardet, 1974) and intrude the Archean basement and late Paleozoic to early Mesozoic dolerites of the Guinea Rise. As elsewhere in Africa, the kimberlites seem closely related to the break-up of Gondwana. The first diamonds were found in 1932 in the Upper Makona valley and commercial production started in 1935 near Baradou. The first kimberlite body was discovered by H. Haggard in 1952 and in the sixties a Soviet team delineated 19 pipes and numerous kimberlite dykes (Kozlov, 1966). Total diamond production from 1935 till today is difficult to estimate because of extensive clandestine activity, but probably amounts to about 3 million carats.

Outside the Kissidougou-Kerouane-Macenta area, diamonds have been sporadically found,

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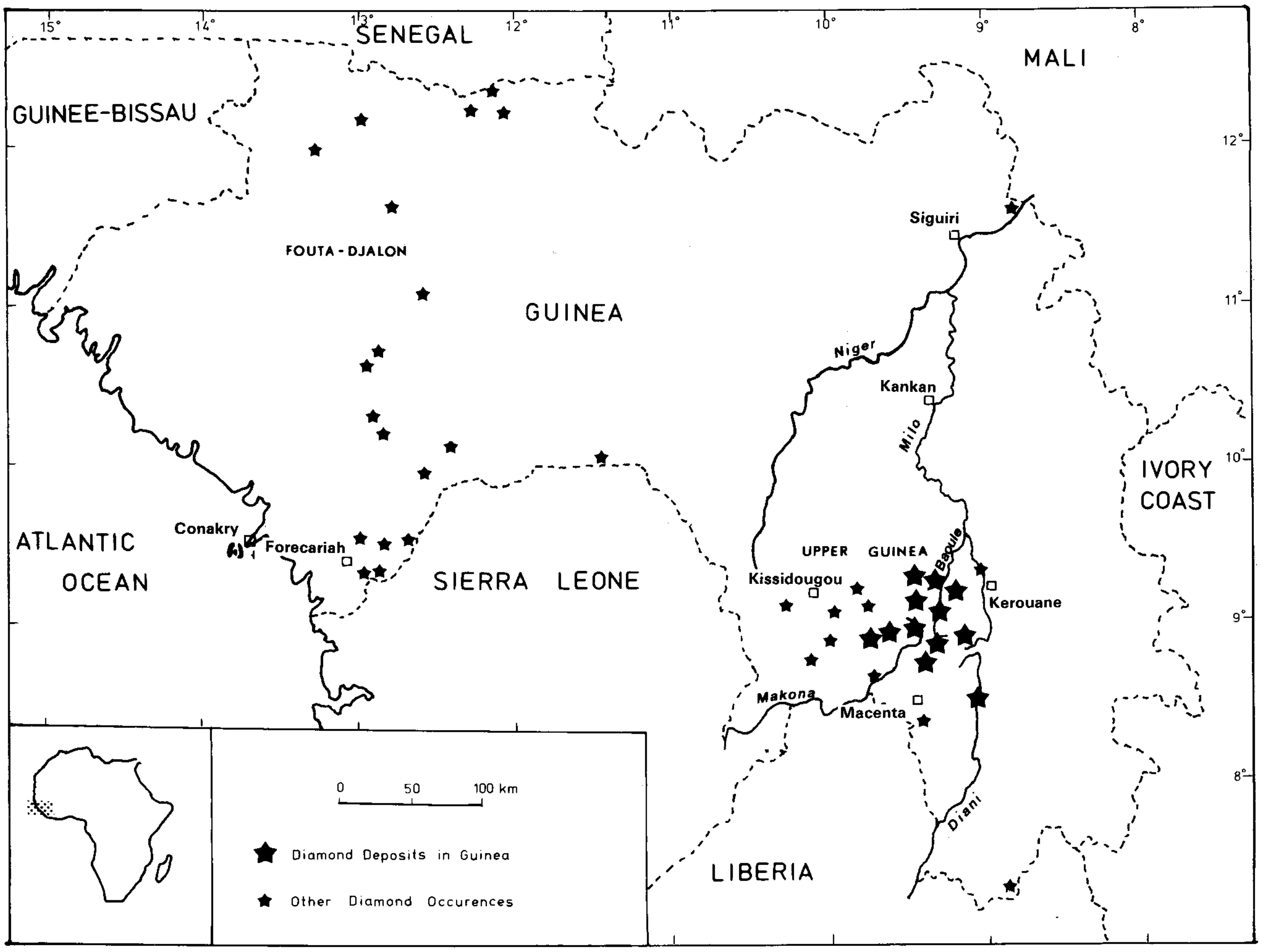

Figure 1.- Diamond occurrences in Guinea.

especially in the Forecariah-Kindia and Fouta Djalon region, but no workable deposits are known. The source of these diamonds are supposedly the conglomerates and grits of the upper Precambrian and lower Paleozoic tabular series covering the Archean and Proterozoic basement. The presence of Cretaceous kimberlites in the Fouta Djalon is yet unproven.

Williams & Williams (1977) indicate the presence of kimberlites in Northern Guinea, but it should be realised that this is only based on the presence of alluvial diamonds.

GEOLOGICAL SETTING

The Guinea Rise, also known as the Leo Uplift or «Dorsale de Man» (Bessoles, 1977; Cahen *et al.,* 1984) refers to the outcropping of rocks of Archean and lower Proterozoic age in the southern part of West Africa. The Guinea Rise is the result of a regional uplift of the West African craton. The Rise is bounded to the west by the Panafrican Rockel and Kasila belts, to the south by the Atlantic ocean and to the east by the Panafrican Togo belt. To the north the Rise is covered by the upper Proterozoic and Paleozoic sediments of the Taoudeni basin (Fig. 2).

Two domains are recognized by Cahen *et al.* (1984) in the Guinea Rise : in the west, the Kenema-Man domain, comprising granitic gneisses with relic zones of supracrustal rocks, and in the east, the Baoule-Mossi domain, showing many outcrops of greenschists. The Kenema-Man domain covers large areas in Liberia, Sierra Leone and Guinea and exposes the deeper parts of the West African craton. The pattern of the supracrustal relic zones remains more or less parallel in a given region and defines regional trends.

The supracrustal relic zones form a large belt, whose trend changes form north-east near the coast, to north in the kimberlitic region of Sierra Leone and Guinea and to north-west near Faranah (Guinea). The Baoule-Mossi domain outcrops in the Ivory Coast, Ghana, Mali, Burkina Faso, in the Kenieba and Kayes windows and in the north-east of Guinea. The numerous occur-

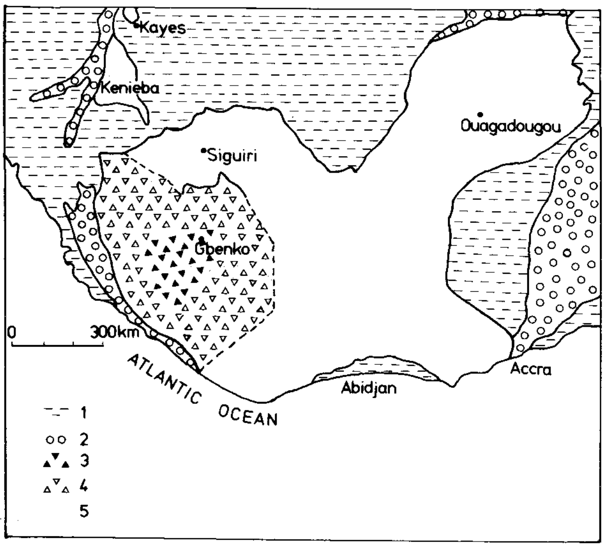

Figure 2.- The Guinea Rise, modified after Bessoles, 1977. (1: Guinea Rise covered by upper Proterozoic to Quaternary formations; 2: Panafrican belts; 3: diamondiferous kimberlite region of the Kenema-Man domain; 4: Kenema-Man domain; 5: Baoule-Mossi domain).

rences of Birrimian sedimentary and volcanic rocks indicate that the West African craton is exposed at a shallower level. The following tectonic thermal events can be recognised (Cahen *et al.,* 1984) :

- The Leonean event, 2960 ± 25 m.y. is the oldest observable in Sierra Leone. Its main trend is east-west;
- The Liberian event, 2753 ± 30 m.y., superimposed on the Leonean event, has a north-south trend.
- The Eburnean event, 2100-1950 m.y., affects mainly the Birrimian belts.
- The Panafrican event, 1100-600 m.y., less precise in time, created the Rockel, Kasila and Togo mobile belts bordering the West African craton.

After the Panafrican event, the southern part of the West African craton remained relatively stable and rigid. Extensional fracturing, accompanied by basic intrusions, was possibly active in the Paleozoic. Obermüller (1941) mentions the presence of gabbros and diabases in Upper Guinea and Dalrymple *et al.* (1975) describe a dolerite belt in northern Liberia having a higher degree of metamorphism than the Mesozoic dolerites.

The major phase of extensional fracturing started in the Mesozoic with the break-up of Gondwana and the opening of the Atlantic Ocean. During Jurassic and Cretaceous times, the North Atlantic Ocean opened around a rotation pole at 66.0° N and 12.0° W (Le Pichon & Fox, 1971). Since 80 m.y. till present times, the pole has shifted towards the north. Le Pichon & Fox (1971) give an average pole position for this period at 79.1° N and 15.7° W. The South Atlantic opened in the Cretaceous around a pole at 21.5° N and 14° W (Le Pichon & Hayes, 1971). Mascle & Sibuet (1974) however give a pole position at 32.0° N and 20.0° W. The opening started in the south and propogated itself towards the north. After the Cretaceous the rotation pole moved to its present position at 67.3° N and 39.5° W. In general we can assume an angle of 30° to 45° between the North and South Atlantic rift axes. The African coastline north of Dakar forms a similar angle with the coastline south of Cameroun. The coastline of the Guinean Gulf and the major equatorial oceanic transfrom faults mark the linking up of the North and South Atlantic rift axes. The Guinea Rise results from a regional uplift associated with the Atlantic rifting. The coastline between Guinee Bissau and Cape Palmas defines the trend of the Atlantic rift axis in this part of Africa.

The Paleozoic and Mesozoic tabular formations of the Fouta Djalon did not originally display preferential zones of weakness in the horizontal plane. The subsequent extensional fracturing associated with the Atlantic rift has created a regular block faulting pattern. The principal trend of the faults is parallel to the coast and the trend of the complementary faults is perpendicular to the coast. This regular block faulting pattern is complicated in the Guinea Rise by the presence of pre-existing zones of weakness, in particular an east-west trend resulting from the Leonean event, a north-south trend from the Liberian event and the trends of the supracrustal belts. The strong lineament trend of N 60° E between the kimberlite region of Sierra Leone and Upper Guinea is more or less perpendicular to the coast and has been interpreted as an extension of the Sierra Leone oceanic transform faults (Williams & Williams, 1977), the genetic relationship probably being the other way round. The Mesozoic dolerite belts near the Liberian and Sierra Leonean coast are subparallel to the coastline and confirm that the maximum tension in the horizontal plane was perpendicular to the coast. Towards the interior, dolerite directions become more variable. An absolute age of 185 m.y. for the dolerites in Liberia was measured by Dalrymple *et al.* (1974). The kimberlites cut the dolerites in Liberia, Sierra Leone and Guinea. Bardet (1974) attributed an age of 95 m.y. to the kimberlites.

The kimberlite trends are N 55° - 65° E in Sierra Leone (Grantham & Allen, 1960; Tompkins & Haggerty, 1984) and N 11° - 32° E in Liberia (Haggerty, 1982), perpendicular to the respective

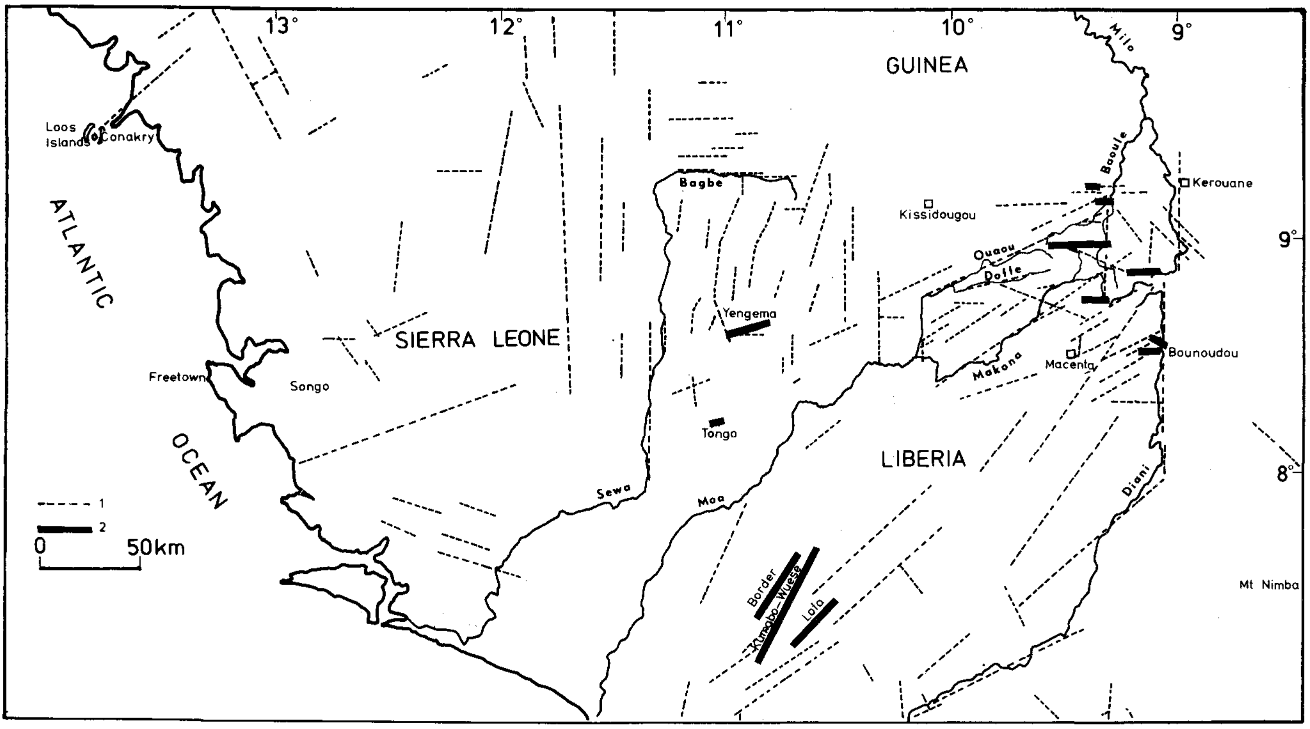

Figure 3.- Relative position of Guinean, Liberian and Sierra Leonean kimberlites. (1: major lineaments; 2: kimberlite trends).

coastlines. It these two trends and even the trend of the Kenieba kimberlitic fractures in Mali are projected into Guinea, they seem to focus into the kimberlite region of Upper Guinea. In West Africa, other kimberlite bodies are known in Kenieba (Mali) and in the Ivory Coast (Bardet, 1974). They are intruded in formations of the Baoule-Mossi domain that underwent the Eburnean event. The presence of diamondiferous lamproites near Seguela (Ivory Coast) recalls a similar relationship as in Australia, where kimberlites occur on the Archean Kimberley Block, while lamproites are located in the surrounding Proterozoic belts (Atkinson *et al.*, 1984). Other magmatic activity associated with the Atlantic rift are the basic intrusive complex of Freetown, the Songo ijolite and the Bagbe alkaline complex in Sierra Leone (Culver & Williams, 1979) and the alkaline complex of the Loos islands in Guinea.

The kimberlite region of Upper Guinea belongs to the Kenema-Man domain of the Guinea Rise. The opening of the Atlantic resulted in extensional faulting and the intrusion of tholeitic dolerites in the region. The extent of erosion since the Cretaceous is probably of the order of 1000 metres (Sutherland, 1984). The present erosion level still contains outcrops of dolerite sills, especially in the eastern part of the kimberlite region.

Obermüller (1941) defined three major geologic terranes in the south-east of Guinea. The Macenta terrane covers the kimberlite region and is dominated by granitic gneiss outcrops with relic belts of amphibolites, quartzites and serpentinites. The Mahana terrane occurs to the east of the Simandou range and is similar to the Macenta terrane. The Simandou belt, 50 to 60 km large and 250 km long in Guinea and continuing into Liberia, runs from Kerouane to Mt. Nimba and separates the Macenta and Mahana terranes. The Simandou belt is made up of supracrustal rocks such as quartzites, iron formations, amphibolites, gneiss, schists and pyroxenites. In Liberia the belt changes direction towards the south-west. Folds are subvertical and isoclinal. The folds are parallel to the overall trend of the belt. A group of left-slip faults cuts the Simandou belt near Kerouane. The faults trend N 135° E and cut the Mesozoic dolerites. The ironstones and quartzites of the Simandou belt form a reference horizon easily visible on Landsat photographs. The left-slip faults displace the quartzites 12.5 km to the west over a length of 25 km. Maximum tension in the horizontal plane seems to be along a N 150° E direction.

KIMBERLITES

Kimberlites are only known to occur in the eastern part of the Macenta terrane. The Simandou belt marks the eastern limit of the Guinean diamond fields. In the western part of the Macenta terrane, close to the Sierra Leonean borders,

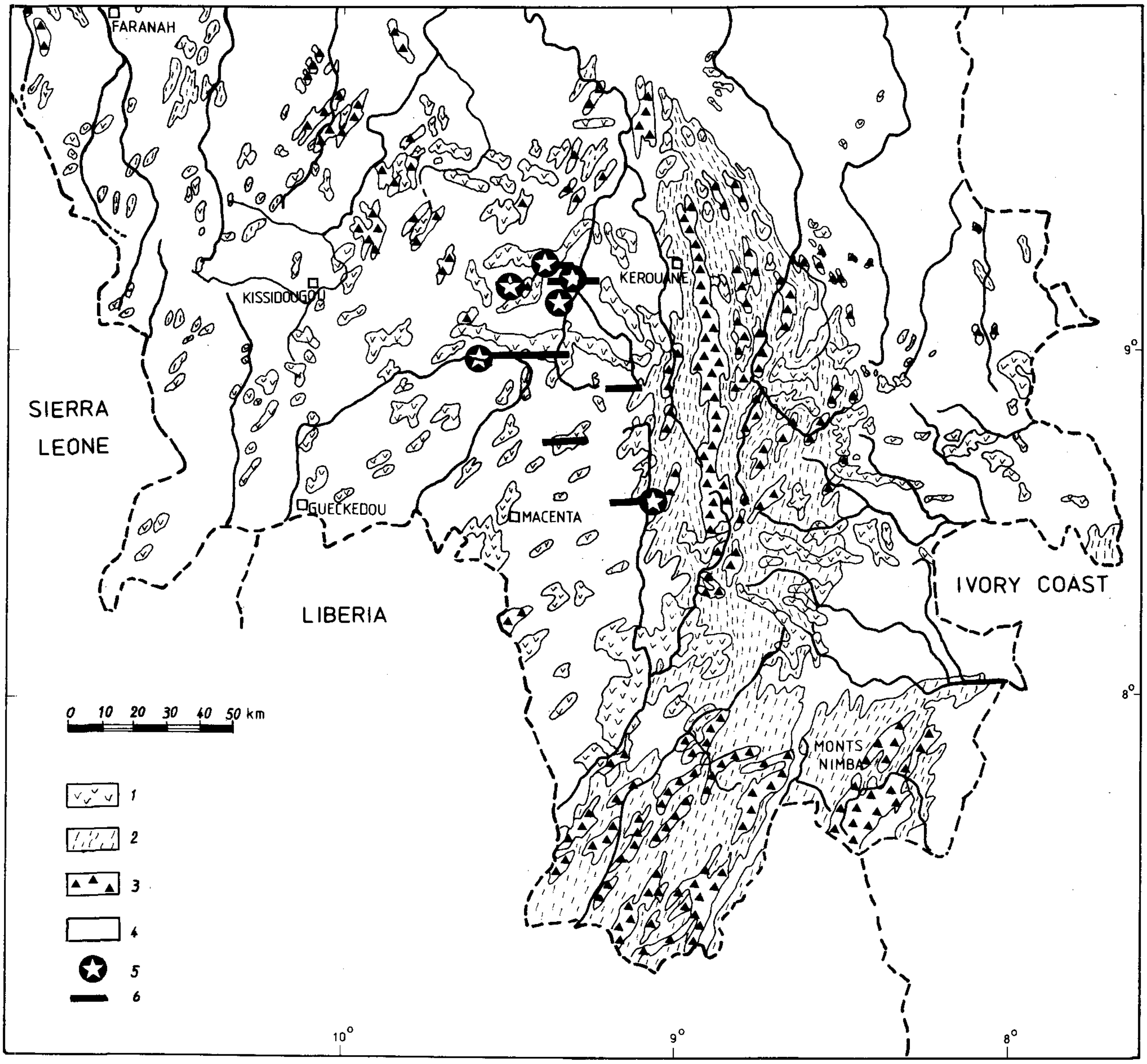

Figure 4.- Geology of Upper Guinea, after IPGAN, 1981.
(1: Phanerozoic dolerites; 2: schists and gneiss; 3: quartzites; 4: undifferentiated Archean, mainly granite-gneiss; 5: kimberlite pipe cluster; 6: kimberlite dyke trend).

diamonds have been found in minor tributaries pointing to the possible presence of kimberlites. So far 19 pipes and numerous kimberlitic dykes and fractures have been identified. Bardet (1956-1974) already noted the strong structural control on kimberlite emplacement. The lineament directions that became tensional with the opening of the Atlantic and the uplift of the West African craton, presented themselves as favourable directions for dolerite and kimberlite emplacement. The major lineaments follow the following directions :

- East-west, resulting from the Leonean Event.
- North-south, resulting from the Liberian event. This direction coincides with the trend of the Simandou belt in the kimberlitic region.
- N 10° - 35° E, perpendicular to the Liberian coast.
- N 125° - 150° E, parallel to the coast and to the Kerouane left slip faults.

The lineaments depicted in Figure 5, should be interpreted as an abstraction of the alignment of several faults over a longer distance. They are easily visible on Landsat pictures and aerial photographs.

The region south-west of Kerouane has the highest density of known kimberlite bodies in Guinea. Considering a square of 50 by 50 km between Gbenko in the north-east corner and Falenko-Ouro in the south-west, the density is about one kimber-

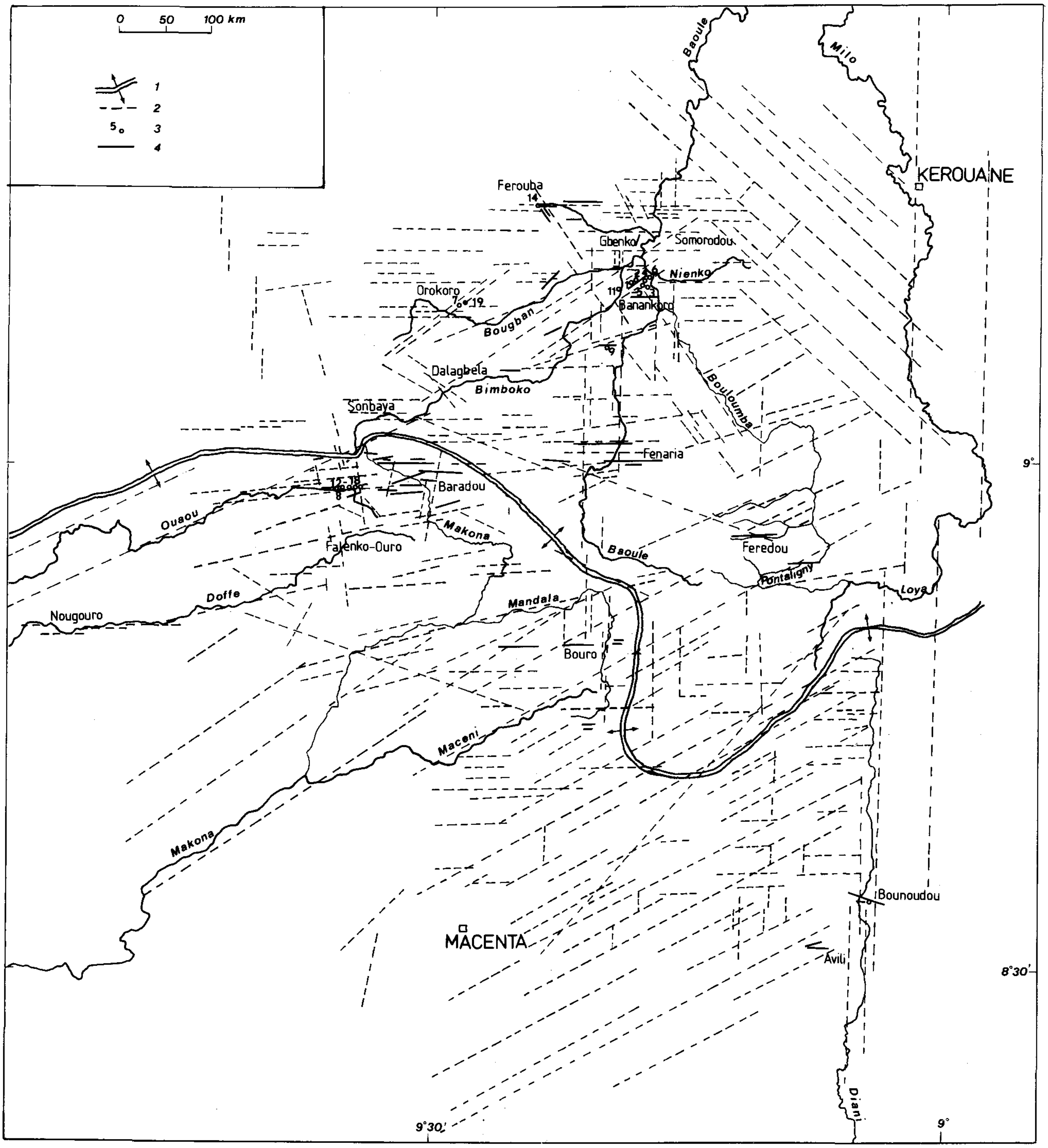

Figure 5.- Structural setting and drainage of Guinean kimberlites.
(1: water-divide between Niger basin to the north and Atlantic basin to the south; 2: lineament; 3: kimberlite pipe, 4: kimberlite dyke).

lite body per 30 square kilometres. The directions of lineaments, dolerites and kimberlites in this square have been studies on a 1:50000 scale. The north-south, N 55° - 65° E and N 125° - 150° E directions, so important on 1:1 000000 scale, are dominated by the sublatitudinal direction. The configuration of lineament, dolerite and kimberlite directions is similar, except for the north-south lineament direction, which seems not exploited by dolerites and kimberlites (Fig. 6). This probably implies that maximum tension in the horizontal plane during dolerite and kimberlite intrusion was perpendicular to the sublatitudinal direction, i.e. along a N 150° - 180° E direction. The sublatitudinal trend of the Guinean kimberlites contrasts with the Sierra Leonean and Liberian trends, which are perpendicular to the coast. This changing trend going land-inwards can also be remar-

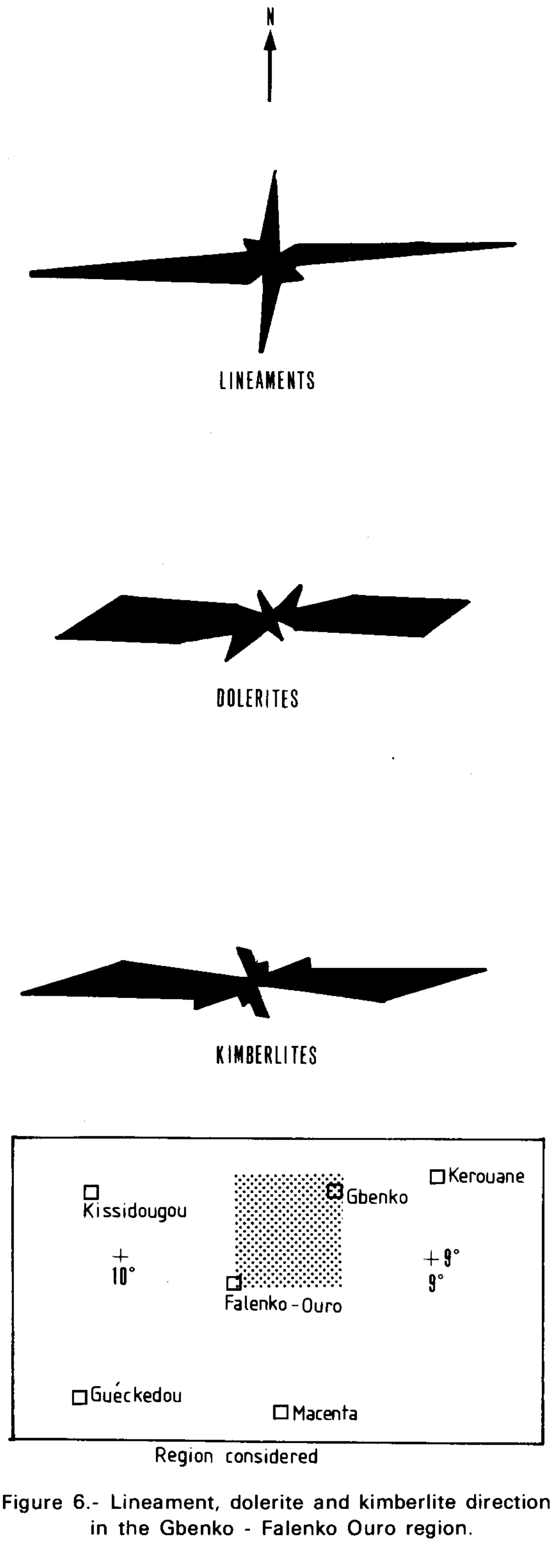

Figure 6.- Lineament, dolerite and kimberlite directions in the Gbenko - Falenko Ouro region.

ked in East and Southern Africa. In Lesotho, closer to the Indian Ocean, the kimberlite dykes trend perpendicular to the Transkei coastline, while towards Kimberley the kimberlite dykes show more variable directions, with especially the sublatitudinal and the direction parallel to the Transkei coast becoming important (Dawson, 1970). In Kenya, kimberlites close to the East African rift trend perpendicular to the main rift (Rombouts, 1985), while kimberlite directions in the Mwadui region of Tanzania are more variable.

The kimberlite pipes in Guinea are often located at the intersection of different lineaments:

- Pipes 1 and 2 at the intersection of the N 60° E and N 90° E lineamments.
- Pipes 3, 4, 5 and 6 at the intersection of the N 0° E and N 30° E lineaments.
- Pipes 7 and 19 at the intersection of the N 60° E and N 90° E lineaments.
- Pipe 14 at the intersection of the N 90° E and N 160° E lineaments.
- Bounoudou pipe at the intersection of the N 0° E, N 90° E and N 124° E lineaments.

Pipes 9, 10, 12, 13, 15, 16, 17 and 19 are blows of N 80° E trending dykes.

Between Gbenko and Tissinkoro, ultrabasic, but non-kimberlitic dykes follow a sublatitudinal direction. In one of the mine cuts near Gbenko such an ultrabasic dyke was seen to cut and displace a kimberlite dyke, indicating a younger age than the kimberlites. The ultrabasic dykes are alkaline lamprophyres displaying gabbroic texture and containing phlogopite, titaniferous amphibole, olivine, as well as diopside and magnetite.

If we define the three perpendicular stress directions $\sigma_1 \geqslant \sigma_2 \geqslant \sigma_3$, we can recognise from the lineament, dolerite and kimberlite directions the following patterns during the uplift of the West African craton:

- Near the coast (e.g. the Fouta Djalon) σ_1 is vertical, σ_2 is horizontal and parallel to the coast and σ_3 is horizontal and perpendicular to the coast.
- In the interior (e.g. the Guinean kimberlite region) σ_1 is horizontal along an east-west direction, σ_2 is vertical and σ_3 is horizontal along a north-south direction.

Most kimberlite bodies were found by the Soviets between 1963 and 1967 (Kozlov, 1966; and unpublished reports and maps at the Ministry of Mines in Conakry) and partial reference to their work has been made in the French and English literature by Bardet (1974), Sutherland (1984) and Meyer & Mahin (1986). The following description of the kimberlites is largely based on Soviet reports. The kimberlite dykes are nearly vertical and in sharp contact with the country rock. Their width varies from a few centimetres to 2-3 metres, but is mostly between 10 and 40 centimetres. Their length varies between 100 and 500 metres. The dykes are grouped in belts 0.8 km wide and 2-4 km long. These belts are sometimes clustered in larger kimberlite dyke zones. The most important zone is sublatitudinal, linking the Upper Makona dykes with the Fenaria dykes and is more than 40 km long and 15 km wide.

Table 1.- Surface area of Guinean kimberlite pipes.

PIPE	SURFACE (m^2)	LOCATION
1	4200	Banankoro
2	7830	Banankoro
3	9900	Banankoro
4	16090	Banankoro
5	4910	Banankoro
6	20170	Banankoro
7 (Antoshka)	95000	Ouroukoro (Bougban)
9	2300	7km south of Banankoro
10	16200	Upper Ouaou
11	6230	Lower Bimboko
12	3700	Upper Ouaou
13	1100	Upper Ouaou
14	30000	Ferouba
15	7700	Upper Ouaou
16	8700	Upper Ouaou
17	3900	Upper Ouaou
18	1800	Upper Ouaou
19	10000	Ouroukoro (Bougban)
Droujba	8470	Bounoudou

(From unpublished Soviet reports at Mines Department in Conakry)

The kimberlite pipes are exposed at their root level and transitions into dykes are often observed. Many pipes are in fact blows within dykes. The outcropping surface of the pipes is small in comparison to the Southern African pipes. The largest pipe, no. 7 (Antoshka), covers 95000 square metres, but most of the pipes cover less than 10000 squares metres (Table 1, based on unpublished reports, Ministry of Mines, Conakry).

According to their texture, three types of kimberlite can be recognized (Kozlov, 1966). The first type are massive dark grey-green rocks. Phenocrysts of olivine, ilmenite, phlogopite and sometimes pyrope are set in a dark matrix. The relative volume of the xenoliths varies from a few % to 20-30 %. Their dimensions are 2-4 cm, but bigger pieces can be present. The xenoliths are often angular and surrounded with rims of dark kimberlite. The second type, the intrusive breccias, contains abundant autoliths (up to 70 %) and xenoliths in a matrix similar to the massive type of kimberlite. It is the most common facies in the Banankoro pipes (pipes 1, 2, 3 and 4) and in certain parts of the Bounoudou pipe. The third type, the porphyritic kimberlites are grey rocks with no xenoliths. Almost all dykes belong to this type. Fragments of porphyritic kimberlite are also present as autoliths in the first two kimberlite types. Phenocrysts are mainly olivine (with serpentine), phlogopite, ilmenite and sometimes pyrope and can be abundant (50-70 %). They are surrounded by a matrix of serpentine, carbonate, phlogopite, magnetite, apatite, monticellite and perovskite (Kozlov, 1966). Apart from country rock fragments, also deep-seated rocks occur as xenoliths, such as olivinites and garnet-pyroxenites (Kozlov, 1966). The olivinites are black rocks with olivine phenocrysts in a matrix of olivine, orthopyroxene and chromite, often altered to serpentine and magnetite. Olivinites are common in the Banankoro pipes 2 and 3. The garnet-pyroxenites are green rocks containing clinopyroxenes (65 %), orthopyroxenes (10 %) and garnets (25 %). The most common indicator minerals are picro-ilmenite (MgO 20-24 %) and garnet. The garnets are of various shades of red, going from orange to violet, and according to unpublished Soviet reports dark green chrome-rich garnets occur in the Bounoudou pipe. All kimberlites in Upper Guinea seem diamondiferous, although of highly variable grade. Dykes have in general better grades than the pipes, probably because of xenolith dilution in the latter.

ALLUVIAL DEPOSITS

The diamondiferous kimberlites of Upper Guinea are covered by two major drainage systems: the Atlantic and Niger drainage (Fig. 5). Distance travelled by the rivers to the Atlantic Ocean is much shorter in the Atlantic drainage and gradients are steeper. Atlantic drainage rivers are continuously capturing the headwaters of the Niger basin rivers.

Diamonds occuring in the Niger drainage are collected towards the Baoule and Milo rivers and finally into the Niger river. The Banankoro, Gbenko, Bougban, Ferouba, Tissinkoro, Fenaria, Flegni, Bimboko, Nienko, Somorodou and Bouloumba deposits are collected towards the Baoule. The Feredou deposits are drained partly via the Faligoua, Mininko and Sarabaya to the Bouloumba and Baoule rivers and partly via the Pontaligny and Loya rivers to the Milo. The kimberlitic diamond sources for the upper Bimboko (Sonbaya) and Mandala (Bouro) deposits were formerly drained towards the Bimboko and Baoule respectively, but are now captured by the Atlantic drainage. The Avili and Bounoudou kimberlites were formerly drained towards the Milo, but are now captured by the south flowing Diani. The Atlantic drainage displays a young relief with incised valleys. Channel directions are stable in time; flats superimpose themselves on terraces and gravels are continuously reworked. Flats have as a result in general better grades than the terraces. In the Niger drainage system relief is more mature with wide valleys and extensive terrace and flat development. In length profile knickpoints are formed by large dolerite sills crossing the valley. Smaller tributaries, especially near the dolerite scarps, show a younger relief and have the same characteristics as the Atlantic drainage rivers (e.g. Ferouba, Sonbaya, Upper Nienko). Alluvial deposition in the mature valleys reflect a progressive shift of the channels towards the south-east, indicating a regional tectonic tilt to the south or south-east. Terraces are better preserved on the north-west side. Flats are not necessarily richer as they do not systematically superimpose themselves on the terraces. Examples are the Bougban, Baoule and middle and lower Bimboko. In northerly flowing rivers (Baoule), channels are forced to flow against the regional tectonic tilt. This back pressure makes the channels meander in wide loops and channel directions are extremely variable in space and time. The resulting gravel and diamond deposition is irregular and unpredictable in plan view. Rivers in the Niger drainage system with a dominantly east-west component (Bimboko, Bougban) have more structured deposits as channel directions remain more or less parallel. An interesting feature of the Bougban terraces is their diamond enrichment in zones characterized by a southward bending of the river valley. In length profile these zones correspond to sinks. Further proof of the regional tectonic tilt is the coincidence of the steepest gradients with a more south-easterly flow direction. Because of continuing capturing from the south, the Niger drainage rivers must have been more important in the past, having a larger drainage area and more sediments to transport. This is reflected in the often much thicker alluvial sequence on the terraces (10 m or more) than in the flats (4-6 m) in the middle Baoule or Bimboko.

The Gbenko area is unique in the sense that almost all major diamond carrying rivers of the Niger drainage are collected here. The dominant trend of kimberlite, dolerite and ultrabasic dykes is east-west. Bedrock highs often follow a N 60° E direction and their boulders form good traps for diamonds. The Baoule flats near Gbenko are 250 to 1000 m wide, and the total width of terrace and flat deposits can reach up to 2.5 km. The alluvial sequence in the flats is 4 to 6 m thick and the present Baoule flows about 1.5 m above bedrock on a gritty or sandy bottom. The alluvial thickness on the terraces can vary from a few cm's to more than 10 m. The gradient of the present river is about 1 m/500 m. The width of the present Baoule channel increases from 25 m just south of the Banankoro kimberlites to 70 m near Gbenko. The Bimboko channel increases its width from 15 m near pipe 11 to 35 m just before joining the Baoule. Water depths vary from 0.5 m to 1.5 m in the dry season, and can reach more than 4 m in the wet season. Terraces sometimes form a continuous slope, but in most areas steps can be recognized. The highest terrace level still preserved is about 25 metres above present base level. Most terrace levels occur 5 to 10 m above present base level. The alluvial sequences on the terraces are lateritised. The alluvial deposits are characterized by a fining upwards sequence. Facies are variable, but in general bedrock, weathered to clay, is overlain by a thin layer of gravel (mostly 30-45 cm thick), followed by a 1-3 m thick grit and sand, covered by silt and clay, 2-5 m thick. Most bottom gravels can be interpreted as (1) a winnowed lag gravel, (2) an aggradational gravel displaying channel fill cross-bedding, (3) a progradational gravel often forming part of a point bar sequence, or (4) a gravel filling scour or plunge pools. The bottom gravel is mostly poorly sorted. Well-rounded clasts are mixed with more angular locally derived clasts. Clasts are predominantly vein quartz, but occasionally bedrock or laterite clasts can form a sizeable proportion of the gravel. On average, about 50 % by weight of the bottom gravel in the flats has a particles size smaller than 2 mm, while about 20 % has a particle size larger than 25 mm. The overlying sand reflects the channel characteristics, with channel fill cross-bedding or point bar set stratification as the most commonly recognized sedimentological features. The silts and clays on top are unrelated to channel hydraulics, as they are flood plain deposits. Occasionally they reflect the filling up of a suddenly abandoned channel.

The heavy mineral concentrate content of the bottom gravels is very variable. The total concentrate content (density > 3) averages 1 % by weight. The concentrate consists of on average 50 % laterite in the flats and 98-99 % laterite in the terraces. The balance is formed by the common black heavy minerals (ilmenite, magnetite, hematite and chromite), corundums, favas and zircons. Other heavy minerals present are monazite, epidote, rutile, anatase, pyrope, non-kimberlitic garnet, columbite, chrome diopside, orthopyroxenes, pyrite, gold and kyanite . Kimberlitic ilmenite can be recognized by its rounded form and «orange peel» surface texture. Close to their kimberlitic source they are often coated with grey leucoxene. Worn corundums and favas have sizes similar to diamonds (by weight mainly between 2 and 4 mm). The sizes of ilmenites and pyropes can be large (> 4 mm) close to their kimberlitic source, but rapidly diminish with distance. Given a local source, zircon, monazite, fresh corundum, epidote, garnet, columbite and pyrite can be occasionally detected in the +4 mm fraction. Pyropes, corundums and especially favas (CFP) correlate best with diamonds. On average, pyropes are 1.4 times, corrundums 4 times and favas 25 times more abundant than diamonds in the bottom gravel.

Confluence areas and tributary channels reworking the main channel gravels are favourable for diamond enrichment. In the flats, best grades are in zones with many big boulders, and on the terraces in large and stable terrace levels. Factors controlling diamond enrichment on a local scale are difficult to diagnose. Local and often ephemeral features such as scour or plunge pools and gullies have often a higher stone and heavy mineral (CFP) density. Planar grades (carats per square metre) are highest in the more mature, well winnowed gravels of the main channel. Stone sizes seem largest in the well winnowed gravels of the valley slopes and main channel lag gravels.

DIAMONDS

The common crystallographic forms among the Guinean diamonds are the octahedron, the dodecahedroid and their macles, while cubes are very rare. The diamonds are largest and best crystallized in the Gbenko and Banankoro area. The Gbenko diamonds consist of 25-36 % octahedra (including distorted forms and flats), 27-28 % dodecahedroids (including distorted, flattened and elongated forms), 7-14 % macles, 4-7 % aggregates, 18-28 % broken and irregular pieces, 0-4 % rounded forms and less than 1 % cubes (Table 2). Clear white and yellow are the most common colour among the Gbenko diamonds. Further browns and greys occur, and more rarely greens. Table 3 lists the colour repartition. Clear white stones amount to 30-34 %, yellow to 37-42 %, brown to 10-16 % and green to 2-4 %. With increasing size, yellows become more abundant, while browns and whites become rarer. Grey stones show all shades from grey to black. Their colour seems to be derived from numerous small inclusions. Table 4 shows the relationship between colour and form. A correlation exists between whites and dodecahedroids, and between yellows and octahedra. Table 5 displays the occurrence of other characteristics such as the

Table 2.- Repartition of forms among Gbenko diamonds.

PARCEL	NO. OF STONES	SIZE (cts)	OCTA-HEDRA	DODECA HEDRA	FLATS	MACLES	CUBES	AGGRE-GATE	BROKEN	ROUNDED	IRREG ULAR
BA12	445	2 - 10	50,0	5,0	20,00	5,0	0	10,0	7,5	0	2,5
		1 - 2	16,4	16,4	32,8	9,8	0	11,5	9,8	0	3,3
		0,5 - 1	17,1	21,8	16,1	11,4	0,5	7,3	18,7	0,5	6,7
		0,25 - 0,50	11,2	43,1	12,1	2,6	0	5,2	17,2	0,8	7,8
		0,10 - 0,25	11,4	51,4	17,1	0	0	0	17,1	0	2,9
		TOTAL:	18,0	27,4	17,8	7,4	0,2	7,0	16,0	0,4	5,8
BA6a	920	2 - 10	59,1	8,6	6,5	10,8	0	8,6	5,4	1,1	0
		1 - 2	43,8	18,8	2,8	13,9	0	7,6	8,3	2,8	2,1
		< 1	18,6	32,7	7,0	14,2	0	2,9	10,4	3,7	10,5
		TOTAL:	26,6	28,2	6,3	13,8	0	4,2	9,6	3,3	8,1
BK3	337	Flats are included in octahedra									
		2 - 10	40,9	9,1	-	13,6	0	6,8	15,9	6,8	6,8
		1 - 2	27,9	25,6	-	11,6	0	11,6	16,3	4,7	2,3
		0,5 - 1	23,4	31,2	-	12,5	0	6,3	12,5	4,7	9,4
		0,25 - 0,50	27,5	36,3	-	6,6	0	5,5	13,2	0	22,0
		0,10 - 0,25	22,6	41,9	-	1,6	0	4,8	12,9	3,2	12,9
		TOTAL:	24,8	26,9	-	9,8	0	7,0	15,1	3,5	12,8

Table 3.- Repartition of colours among Gbenko diamonds.

	SIZE	WHITE	YELLOW	BROWN	GREY	GREEN
BA12	2 - 10 cts	15.0	65.0	7.5	10.0	2.5
	1 - 2 cts	24.2	33.9	12.9	21.0	8.1
	0.5 - 1 ct	30.6	34.7	17.6	12.4	4.7
	0.25 - 0.05 ct	36.5	35.7	20.9	3.5	3.5
	0.10 - 0.25 ct	54.3	34.3	8.6	2.9	0
	TOTAL:	31.7	37.5	16.2	10.3	4.3
BA6a	2 - 10 cts	13.3	62.2	4.4	14.4	5.6
	1 - 2 cts	35.4	34.7	14.6	11.1	4.2
	< 1 ct	31.8	41.0	15.7	8.3	3.2
	TOTAL:	30.5	42.1	14.5	9.3	3.6
BK3	2 - 10 cts	22.2	55.6	0	22.2	0
	1 - 2 cts	37.8	32.4	5.4	21.6	2.7
	0.5 - 1 ct	34.5	33.6	11.5	20.4	0
	0.25 - 0.50 ct	32.6	38.9	11.6	12.6	4.2
	0.10 - 0.25 ct	37.7	30.2	20.8	5.7	5.7
	TOTAL:	33.7	37.3	10.5	16.0	2.4

presence of rounded or sharp edges, frosting and pitting, and abrasion. Most diamonds are rounded at the edges. Frosting is especially common among the dodecahedroids. Abrasion is rare. The above observations seem to indicate that the initial population at the source in the upper mantle consisted of white or yellow octahedra with their associated forms such as flats and macles. The bigger stones contain more colour centers and are thus more often yellow. During kimberlite explosion, the diamonds came under severe chemical attack. Resorption transformed the octahedra in dodecahedroids (Orlov, 1973). Rounded faces develop at the 12 edges of the original octahedron and dissolution and development of the rounded dodecahedroid faces proceeds at the expense of the original octahedron faces. As smaller stones have relatively more surface area to volume, dodecahedroids occur more frequently among the smaller sizes. The dodecahedroids can be flattened or elongated, giving them an ellipsoid outline. Outside the Gbenko-Banankoro area, resorption has been more pronounced. The frequency of dodecahedroid and irregular frosted stones increases while average stone size decreases in comparison to the Gbenko stones. Overall stone quality decreases southwards, with inclusions and brown and grey colours becoming more frequent. In comparison to other diamond mines such as the South African Finsch, Koffiefontein and Premier pipes (Harris *et al.*, 1975), the Gbenko diamonds have a lesser percentage of irregulars. The South African pipes show the same relationship as Gbenko between size and form. With increasing stone size, octahedra become more numerous at the expense of dodecahedroids, brown stones decrease, while macles remain constant or increase. The alluvial deposits of Namaqualand and Namibia look more like Gbenko, because irregulars have been sorted out by alluvial selection. The Mwadui pipe in Tanzania shows mostly dodecahedra. Octahedra amount to less than 1 % (Grantham & Allen, 1960), indicating a more advanced state of resorption. The Sierra Leone diamonds are mostly sharp edged octahedra and macles, with few dodecahedroids, pointing to limited resorption (Grantham & Allen, 1960). The colour of the Sierra Leone diamonds is similar to the Gbenko diamonds, except that coated stones are common in Sierra Leone.

Table 4.- Colour versus form (BA12 parcel).

FORM	WHITE	YELLOW	BROWN	GREY	GREEN
OCTAHEDRON	30.8	51.3	6.4	6.4	5.1
DODECAHEDRON	48.3	27.5	15.0	7.5	1.7
FLAT	29.5	46.2	9.0	10.3	5.1
MACLE	31.3	43.8	9.4	9.4	6.3
BROKEN	18.6	28.6	34.3	12.9	5.7
AGGREGATE	12.9	38.7	22.6	19.4	6.5
IRREGULAR	26.1	34.8	21.7	17.4	0

Table 5.- Other form characteristics of the Gbenko diamonds.

PARCEL	INCLUSION FREE (Naked eye)	- 1mm INCLUSION	+ 1mm INCLUSION	OPAQUE	SHARP EDGED	FROSTED	ABRADED
BA12	18.4	22.2	52.1	7.2	3.6	29.7	7.0 %
BA6a	29.9	23.8	46.2	6.0	6.6	29.3	8.4 %
BK3	21.1	19.0	57.1	2.7	7.1	43.8	2.1 %

The average stone size of plus 2 mm diamonds is 0.8 ct in Gbenko and Banankoro, and varies between 0.1 and 0.5 ct in the other Guinean diamond deposits. The stone size distribution in the kimberlites and in homogeneous alluvial deposits is well approximated by two-parameter lognormal distributions. Mixed lognormal distributions occur in confluence areas of diamond-carrying rivers with markedly different size distribution characteristics and when diamonds of different sedimentological environments are considered. Diamond sizes in kimberlites and in an alluvial environment can be said to be subject to the theory of proportionate effect (Kapteyn, 1903; Aitchison & Brown, 1957). A variate subject to a process of change is said to obey the law of proportionate effect if the change in the variate at any step of the process is a random proportion of the previous value of the variate. If steps are sufficiently large, the result will be a two-parameter lognormal distribution for the variate. This process is active during crystallisation, in an ascending kimberlite magma and in an alluvial environment. In an alluvial bottom gravel, the maximum stone size can only decrease (by breakage or wear) and the minimum stone size remains constant at 0.05-0.10 carats. Hydraulic equivalence will disperse smaller diamonds in the top gravel or sand. Under these circumstances, both the mean and standard deviation decrease during alluvial transport. Sutherland (1982) suggested an exponential decrease of the average stone size with distance in an alluvial environment. His model is :

$$z = z_0 \exp(-a\sqrt{d}) \qquad (1)$$

with z average stone size in carats at distance d in km and z_0 the average stone size in carats at the source. To apply this model, sampling data should be available over a considerable length of the river and diamonds should come from a single source. These conditions are rarely satisfied in Guinea. Only data from the Bimboko river between Sonbaya and Dalagbela meet these conditions. The fitted model is :

$$0{,}42 = 0{,}21 \exp(-\,0{,}2\sqrt{d})$$

In comparison with other environments (e.g. Sierra Leone) the stone size decay rate is high.

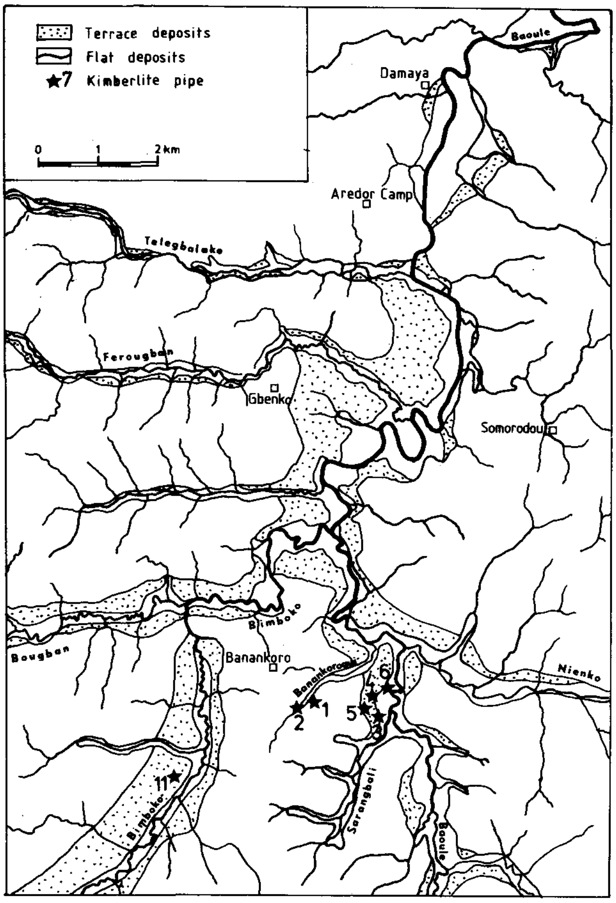

Figure 7.- The Gbenko - Banankoro diamond deposits.

This could be explained by the longer transit times for the stones with distance in the Niger drainage system, due to the tectonic tilt acting against the overall drainage direction. Decay rate in rivers of the Atlantic drainage system should be less and maybe similar to Sierra Leone. Sutherland (1982) mentions a decrease in average stone size along the Sewa from almost 1 ct at the source to 0.2 ct 170 km downstream, with a = 0.13. In other places Sutherland (1982) gives :

Namibian coast: $z_0 = 1.93$ and $a = 0.16$
Kasai (Zaire) : $z_0 = 0.92$ and $a = 0.18$
N'Goere
(Central African Republic) $z_0 = 0.69$ and $a = 0.18$

In the Gbenko and Banankoro area almost all tributaries are diamond carrying and the above quantitative approach cannot be applied. Nevertheless the bulk of the diamonds are coming from the kimberlite cluster just south of Banankoro. The Bimboko and Baoule river deposits of the Gbenko-Banankoro area can be subdivided in supposedly homogeneous areas (stone size wise) between major diamond carrying tributaries (Fig. 7). The stone sizes from exploration data can be grouped within these areas to check on any downstream trends. The following areas have been defined:

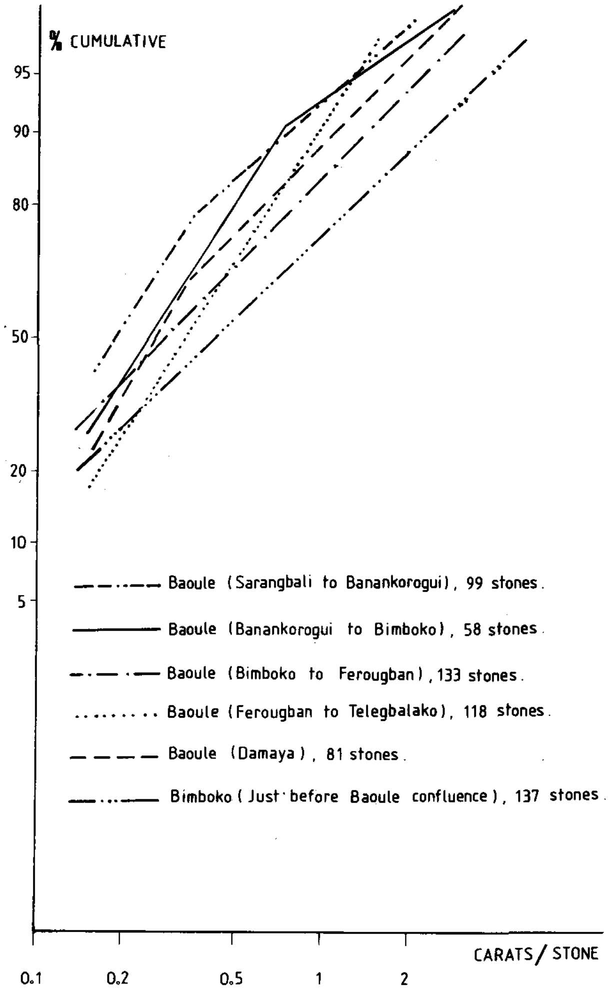

Figure 8.- Cumulative stone size distributions of the Gbenko - banankoro diamond deposits.

- Baoule between Sarangbali and Banankorogui
- Baoule between Banankorogui and Bimboko
- Baoule between Bimboko and Ferougban
- Baoule between Ferougban and Telegbalako
- Baoule of the Damaya flats
- Bimboko just before the Baoule confluence.

The stone size distribution for these areas are graphically represented on a lognormal plot in Fig. 8 : The steeper the slope of the lognormal curve, the better sorted the population and the more to the right the curve, the larger the average stone size of the population. The plot shows that the Bimboko offers the highest input of large stones within the Gbenko area. The influence of the Bimboko input is visible till beyond the Telegbalako. Only at Damaya are the stone size characteristics of the Baoule deposits becoming similar to the Baoule deposits upstream of the Bimboko confluence. The mixed nature of the stone size distribution of the Baoule deposits between the Sarangbali and the Bimboko point to two different stone size populations : one population of large stones derived from the nearby kimberlite pipes and dykes, and a population of smaller stones derived from a source further upstream (pipe no. 9 and Fenaria). The Damaya deposits also show a mixed distribution due to the input from kimberlite dykes known to occur in the Somorodou area.

GRADE ESTIMATION

From an economic point of view the alluvial deposits in the Gbenko-Banankoro area are the most interesting, both in value and volume. The high average stone quality - 93 % of the stones are of gem quality - and the high average stone size (0.7 -1 ct/st) allow very low grade deposits to be mined. At present no kimberlite bodies are exploited. The value contribution of stones smaller than 2 mm (mostly less than 0.1 ct) is negligible, as 50 % of the revenue is realized on stones larger than 5 ct and 90 % of the revenue on stone larger than 1 ct. Almost all plus 2 mm stones are concentrated in the lower 45 cm of the alluvial sequence and in the upper 15 cm of the clayey bedrock because of penetration along fissures. The concentration of plus 2 mm stones in a narrow horizon of 60 cm thick reduces grade estimation to two dimensions and planar grades can be used. The grade of an alluvial deposit, expressed as carats per square metre, is obtained from a grid of exploration samples covering the deposit. To facilitate calculations the grid should ideally be regular and the samples of unit area. Given the high stone value and low stone density, barren samples are common during exploration, even in reserve blocks.

The average carat grade of a deposit is function of the average stone size and the average stone density within the deposit. The stone density is discrete and can be expressed by a modified Poisson distribution, proposed by Sichel (1973) :

$$\phi(r) = \sqrt{\frac{2\alpha}{\pi}} \exp\left(\alpha\sqrt{1-\frac{2\beta}{\alpha}}\right) \frac{\beta}{r!} K_{r-1/2}(\alpha) \qquad (2)$$

with $K_{r-1/2}$ (α) the modified Bessel function of the second kind of order (r - 1/2) and with the two parameters $\alpha > 0$ and $\beta > 0$. Other distributions previously proposed to describe the occurrence of diamonds in a deposit, such as the three parameter lognormal model by Applin (1972) and the simple Poisson distribution by Phillips (1971), are less flexible and fail to explain the typical long tail of the stone density distribution in an alluvial or littoral environment. Sichel's model implies that diamonds are enriched in clusters, which relative to the grid density can be considered to be randomly distributed. A third parameter θ can be defined with

$$\theta = \frac{2\beta}{\alpha} \qquad (3)$$

which characterizes the tail of the modified Poisson distribution. Parameter θ varies between 0 and 1. The closer to 1 the more pronounced the cluster effect is and the closer to 0 the more the distribution becomes like a simple Poisson distribution. In the alluvial environments of Upper Guinea θ is highly variable, with the lowest values (0.2 - 0.4) in immature aggradational gravel filling up the space between boulders of several metres diameter, and with the highest values (more than 0.9) in well winnowed terrace lag gravels. In the beach deposits of Namibia Sichel (1973) found $\theta = 0.97$.

If barren samples are common, the parameters of Sichel's modified Poisson distribution are well estimated by :

$$\alpha = \left[-\ln\phi(0)\right]\left[1-\frac{\ln\phi(0)}{2(\bar{r}-\ln\phi(0)}\right] \qquad (4)$$

and

$$\beta = \frac{\bar{r}}{\alpha}\left(\sqrt{\bar{r}^2+\alpha^2}-\bar{r}\right) \qquad (5)$$

with Φ(o) the observed proportionnal frequency of barren samples and r the observed average number per sample unit. The Pearsonian shape coefficients of the sampling distribution of the mean number of stones per sample unit are (Sichel 1971, 1973) :

$$B_1(\bar{r}) = \frac{\left[2(2-\theta)+\theta^2\right]^2}{2n\bar{r}(1-\theta)(2-\theta)^3} \qquad (6)$$

$$B_2(\bar{r}) = 3 + \frac{8+4\theta+4\theta^2-\theta^3}{2n\bar{r}(1-\theta)(2-\theta)^2} \qquad (7)$$

with n number of samples.

As discussed before, the stone size distribution is well approximated by a two-parameter lognormal distribution :

$$f(z) = \frac{1}{\sqrt{2\pi}}\,\frac{1}{\sigma z}\exp\left[-(\ln z - x_e)^2/2\sigma^2\right] \qquad (8)$$

with z the stone size in caract weight, σ^2 the logarithmic variance and x_e the logarithmic mean. From production records it was found that the arithmetic mean of the individual stone sizes of exploration samples is the best estimator for the average stone size in a deposit. Sichel's t-estimator (Sichel 1966, 1973) often underestimates the average stone size, which is probably due to the small numbers of stones available.

The average planar grade of a deposit is obtained from :

$$g_a = \frac{\bar{r}\bar{z}}{A} \qquad (9)$$

with r average number of stones per sample unit, z the average stone size and A the unit sample area'. The variance of the grade estimator can be approximated by (Sichel, 1973) :

$$\mathrm{VAR}(g_a) = \frac{\bar{z}^2}{A^2 n}\left[\frac{\bar{r}(2-\theta)}{2(1-\theta)} + \bar{r}\sigma^2\left(1+\frac{\sigma^2}{2}\right) - \frac{\sigma^4}{2}(1-\phi(0))\right] \tag{10}$$

with n number of samples. While the variance of the grade estimator is largely influenced by the variance of the mean of the stone density distribution, the variance of the stone sizes is not negligible, especially closer to the kimberlite source. The shape of the grade distribution is defined by the shape of the stone density distribution. To obtain confidence limits, the Pearsonian shape coefficients of the stone density distribution can be used with the tables given by Johnson *et al.* (1963). The categorization of reserves and resources can be based on the confidence limits. In the Gbenko-Banankoro mine workings it was found that the 80 % confidence limits are the most practical. Proven reserves are the blocks with a lower 80 % confidence limit equal or above the economic cut-off grade, while uneconomic blocks have an upper 80 % confidence limit below the economic cut-off grade.

Blocks which do not satisfy the above two conditions are considered possible or marginal reserves. Infill sampling along a denser grid often narrows the confidence limits till one of the two conditions are met, but sometimes blocks remain in the marginal category, because their real grade is indeed marginal. For computation, it was found easier to avoid the tables of Johnson *et al.* (1963) by approximating the percentage points with a trend surface :

$$80\%\,\mathrm{LOWER} = g_a + \sigma_{g_a}\left(1{,}282316 + 0{,}1058648\sqrt{B_1(\bar{r})} - 0{,}013125\,B_2(\bar{r})\right) \tag{11}$$

$$80\%\,\mathrm{UPPER} = g_a + \sigma_{g_a}\left(1{,}434705 + 0{,}1493471\sqrt{B_1(\bar{r})} - 0{,}0476325\,B_2(\bar{r})\right) \tag{12}$$

with

$$\sigma_{g_a} = \sqrt{\mathrm{VAR}(g_a)} \tag{13}$$

If samples have a different support or a different area of influence (no regular grid), the grade of each sample should be weighted accordingly. The grade distribution of the samples can then be approximated by a Pearson type distribution (Elderton & Johnson, 1969), the shape being described by the Pearsonian shape coefficients :

$$B_1(x) = \frac{m_3^2}{m_2^3} \tag{14}$$

and

$$B_2(x) = \frac{m_4}{m_2^2} \tag{15}$$

with m_2, m_3, m_4 respectively the second, third and fourth central moments of the sample distribution. The Pearsonian shape coefficients of the distribution of the mean are given by :

$$B_1(g_a) = \frac{B_1(x)}{n} \tag{16}$$

and

$$B_2(g_a) = 3 + \frac{B_2(x)-3}{n} \tag{17}$$

with n number of samples. Experience has shown that the Pearsonian shape coefficients indicate a grade distribution curve intermediate between the Pearson Type III and Type V distribution. The confidence limits of the average grade of a block can be approximated by the formulas (11) and (12), replacing the Pearsonian shape coefficients by (16) and (17).

The value of individual sample results should not be used as a criterion in defining block limits. Barren samples form a legitimate part of a statistical population and avoiding them at the borders will result in an overestimation of the grade of the block. Block limits should be defined by an independent observation such as bedrock contouring, which allows the recognition of homogeneous gravel deposits. The bias introduced by avoiding barren samples at the borders has been compensated by a high-value cut-off in other methods such as the three-parameter lognormal model (Applin, 1972). The use of heavy mineral counts in defining block limits was found impractical in the Gbenko-Banankoro area. The corundum-fava-pyrope counts indicate a similar spatial randomness as for diamonds with the heavy mineral (CFP) grain density about 30 times richer than the diamond stone density.

By the above methods an average grade and its variance and confidence limits can be assigned to a mining block, but this does not necessarily mean that the grade and variance are distributed uniformly over the whole block. To predict the grades and variance of selective mining units within a mining block, the spatial or structured component of the variance need to be quantified (Matheron, 1962; 1963; David, 1977; Jounel & Huijbregts, 1978). The spatial component of the variance can

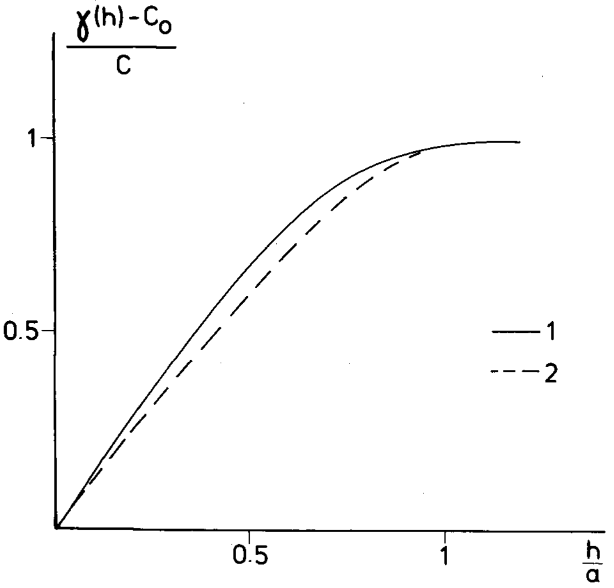

Figure 9.- Spherical (1) and circular (2) semivariograms.

be represented by the semivariogram function :

$$\gamma(h) = \frac{1}{2n} \sum_{i=1}^{n} (x_i - x_{i+h})^2 \qquad (18)$$

i.e. the mean squared difference between two samples at distance h. The above definition of the semivariogram is very sensitive to outliers. Semivariograms of discrete distributions, where many barren samples are present, lack robustness. Semivariograms become useful when the grades follow a continuous functions, with at least ten diamonds in each sample being recovered. Semivariograms need to be calculated in both an across and an along channel direction to determine the anisotropy factor. In both directions, the spherical model of the semivariogram can be applied (David, 1977) :

$$\gamma(h) = C\left[\frac{3h}{2a} - \frac{h^3}{2a^3}\right] + C_0 \qquad \text{for } h \leq a \qquad (19)$$

$$\gamma(h) = C + C_0 \qquad \text{for } h > a \qquad (20)$$

with C = spatial component of variance

C_0 = chaotic component of variance (nugget effect)

α = range.

When planar grades are considered, a circular model would be more fitting :

$$\gamma(h) = \frac{2C}{\pi}\left[\frac{h}{a}\sqrt{1-\frac{h^2}{a^2}} + \arcsin\left(\frac{h}{a}\right)\right] \qquad (21)$$

$$\text{for } h \leq a$$

$$\gamma(h) = C + C_0 \qquad \text{for } h > a \qquad (22)$$

Figure 3 shows that the spherical and circular models are almost identical. As soon as the semivariogram is known, the theory of reginalized variables (kriging) can be applied. Accepting second order stationarity, the grades and variance of selective mining units can be estimated (David, 1977; Journel & Huijbregts, 1978).

In the case of discrete distributions, where semivariograms lack robustness, probability tests can be applied along sampling lines to check if adjoining samples are independent of each other, i.e. spatially random. The problem can be simplified to two mutually exclusive states, nil (no diamonds in sample) or positive (at least one diamond in sample). This reduces the problem to a «head or tail» case of probability theory, with the % chance of outcome given by the % of nils within the area under consideration. Along lines probability theory can be extended to a sequence of outcomes by applying runs tests. A run can be illustrated as follows : take heads (h) or tails (T), possible sequential outcomes are :

HHHHHHHTTTTTTT = 2 runs, highly unlikely,
or HTHTTHTHHTHHTT = 10 runs, more likely.

The first extreme case would indicate order in the data, the second only randomness. The possible outcomes can be quantified as follows (Davis, 1973) :

$$U = \frac{2n_1 n_2}{n_1+n_2} - 1 \qquad (23)$$

with U the expected number of runs if random and n_1 and n_2 the number of nils and positives respectively.
The variance is given by :

$$S_U^2 = \frac{2n_1 n_2(2n_1 n_2 - n_1 - n_2)}{(n_1+n_2)^2(n_1+n_2-1)} \qquad (24)$$

Applying runs tests and semivariogram analysis result in the following three cases :

1. Runs test indicate a random distribution.
2. Runs tests indicate non-randomness and the semivariograms in an along and across channel direction allow the spatial component of the variance to be quantified.
3. Runs tests indicate non-randomness, but the semivariograms are too erratic to define the spatial component of the variance.

A computer program was developed whereby each data point was deleted in turn an its value predicted from the rest of the data using different distance weighing functions, rotations and anisotropy factors. This cross-validation exercise invariably showed very poor fits for case 1 and 3 deposits, illustrating the poor spatial definition.

On a regional scale, case 3 is the most common. Gravel and diamond deposition is well structured if the channel direction remains constant in time. This is the case for the Atlantic drainage rivers (Doffe, Makona, Ouaou) and for those rivers in the Niger basin having a dominantly east-west component (Bougban, Bimboko, Ferougban). If the deposits are very rich stone density-wise with at least ten stones per sample, case 2 becomes applicable.
Case 1, less important on a regional scale, is from an economic point of view the most interesting as it covers the high stone quality deposits of the Gbenko and Banakoro area. The random case seems associated with northerly flowing rivers in the Niger basin, flowing agains the regional tilt with channel directions very variable in space and time. As discussed before the stone density distribution of case 1 can be approximated by a modified Poisson distribution. Sichel's modified Poisson distribution is created by a parent process of randomly distributing clusters in space; the point density of each cluster (the daughter process) follows a distribution intermediate between a Pearson III and V curve, similar to lognormal distributions. Lognormal distributions can be very skewed, and so can be the point density distribution of each cluster. To clearly define the diamond distribution in a given block, we need to know the following spatial parameters of the modified Poisson distribution :

- The size and density of the clusters
- The mean and variance of the stone density within the clusters.

Quantitative estimation of the above parameters based on the results of an exploration grid of say 50 m x 50 m is impossible. In practice a semi-quantitative estimation of the spatial parameters was obtained from production records of selective mining units. Clusters seems to cover between 100 and 350 m^2 in the Gbenko area. Within each cluster the density or grade of the diamonds follow a lognormal distribution, with grades varying from 0.05 to 1 ct/m^2 occurs. As any practical exploration grid remains far short of one sample per 500 m^2, the enriched clusters cannot be located precisely and the grade of selective mining units cannot be predicted. This model explains the success of the private and clandestine miners. In promising areas, their prospecting pits are very dense (often one pit per 25 m^2), allowing them to pick up the richer clusters of about 100 to 350 m^2. In practice the grades of selective mining units is qualitatively estimated with a nine point moving average.

Similarly, for case 3 where runs tests indicate non-randomness but where no robust semivariograms can be obtained, the grades of selective mining units can only be estimated qualitatively with moving averages. On the Bougban deposits, which show non-randomness in an across channel direction, and on the middle Bimboko deposits, which show non-randomness in an along main channel direction because of enrichment in tributary channels, the value of individual samples can be used as a criterion in defining block limits without introducing a bias. The block limits based on sample results mostly coincide with breaks in slope of the terrace levels. Within such a defined block the sample grades have been shown by runs tests and semi-variograms to be spatially random with no structured component of the variance, and Sichel's (1973) method can be used to define the grade of the block with its confidence limits.

MONETARY VALUATION

The monetary value of individual stones in a deposit follows a two-parameter lognormal distribution, with a very high variance if the average stone size, variance and gem content are high (Fig. 10), as is the case in the Gbenko-Banankoro area. Commercial grading involves some subjectivity,

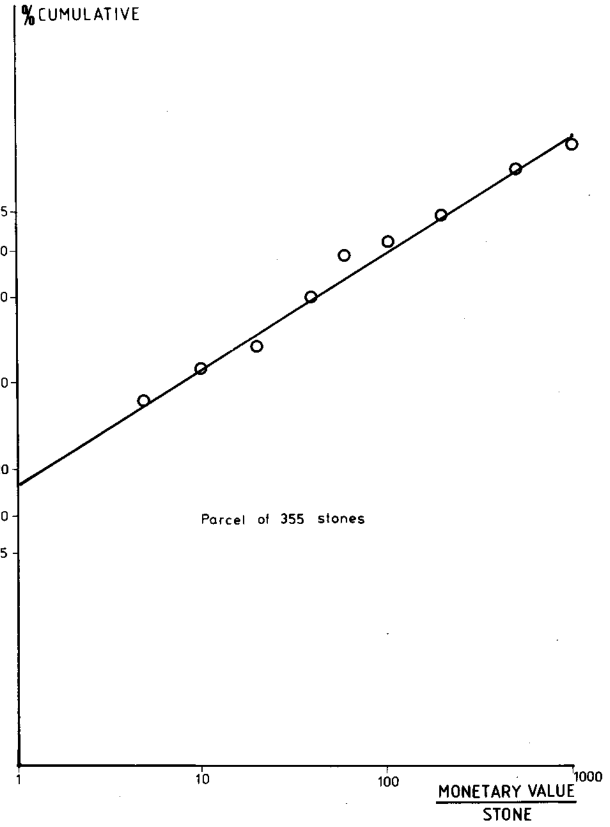

Figure 10.- Cumulative value per stone distribution.

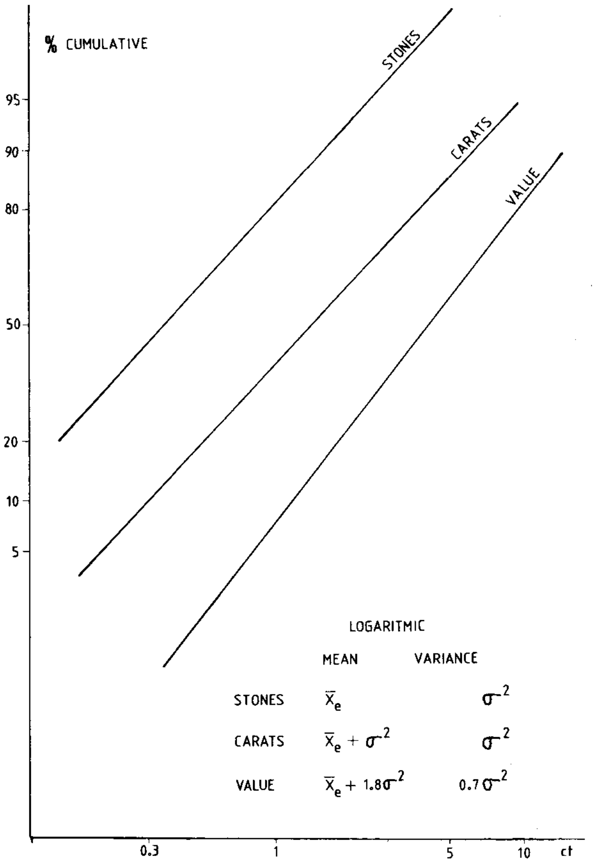

Figure 11.- Cumulative distribution of number of stones, carat weight and value per size class (parcel of 23813 carats).

and a fortiori the whole sale process. However for mine planning purposes it is imperative to distill some objective parameters describing the value of the stones. They will be almost certainly an over-simplification of the whole valuation process if they want to be practical. The simplest approach is to assume similar quality distributions per size class for blocks belonging to a homogeneous area stone quality wise. The value will then only depend on the average stone size and the stone size variance. Quantitative valuation would be possible if a formula existed relating value to the parameters of the lognormal size distribution. Two approaches seem possible, the lognormal and the polynomial one. The polynomial solution is suggested by Sichel (1973), but fitting the value curve of the Gbenko diamonds to a polynomial is difficult, unless the curve is truncated at 0.5 and 9 ct. These truncation points have to be entered into Sichel's integral formula. The lognormal approach starts from the observation that the carat weight distribution is a moment distribution of the stone size distribution and from the assumption that the value distribution would be a similar higher moment distribution. However, the value distribution of the Gbenko diamonds has less variance than the stone size of carat weight moment distribution (Fig. 11). Again, this approach seems best for stone sizes between 0.5 and 9 ct. The major problem for both approaches is the best possible estimation of the logarithmic mean and variance of the stone sizes. For grade estimation, the most important variance is the stone density variance, but for value estimation the stone size variance becomes the most important. The problem with stone populations of exploration samples is the sensitivity of parameter estimation to outliers. For this reason, value estimation becomes only practical on parcels of at least 500 stones. In practice, no robust formula has been found relating value to the logarithmic stone size parameters and the carat weight proportional frequency per size class is multiplied by the average value of the diamonds per size class and summed to obtain the average value per carat. This method is similar to the one described by Oosterveld (1972).

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