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Synopsis of Lunda geology, NE Angola: Implications for diamond exploration

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Key-words: Congo Craton; structural control of the kimberlites / lamproites emplacement; South Atlantic opening; break-up of Congo Craton; evolution of Congo Basin; Kwango Group; Kalahari Group; Quaternary detritus deposits; diamondiferous resources.

Abstract: In the present synthesis, the geology of Lunda (NE Angola) is presented and discussed with the objective of providing a better understanding of the regional occurrence of primary and secondary diamond deposits. The huge regional diamondiferous potential is viewed in a global perspective, firstly based on the edification of the Congo Craton from an Archaean nucleus, till several mobile belts accreted successively to that core. In this cratonic block the geothermal gradient variation and the stability curve of diamond are determinant both in the genesis and the transportation of this precious mineral up to the surface.

Following this, we analyse the tectonosedimentary evolution of the Congo Basin, an enormous depression in central Africa, where the deposition of thick sedimentary sequences is a consequence of an endorheic drainage, that begins in the upper Palaeozoic and has its maximum expression in the Meso-Cenozoic. The sedimentological processes, essentially terrigenous and continental, is controlled by the pre-Atlantic deformation of the Congo Craton and reaches a critical point with the opening of the South Atlantic since the Cretaceous. The oceanic rifting produces important tectonic consequences in the African plate, reactivating structures from previous orogenic cycles. These structures exerted the control of kimberlite emplacement and associated alkaline ring structures.

The sedimentological analysis and the lithostratigraphic definition of post-kimberlites sedimentary units are emphasised: Kwango Group, Kalahari Group and Quaternary deposits, formed in successive erosion/deposition cycles with consequent reworking of its diamond content. These are viewed with an exploration and economical potential.

Finally, a critical balance is made and the economical consequences of these vast diamondiferous resources are discussed based on future economic perspectives.

Palavras-chave: Cratão do Congo; controlo estrutural da implantação de kimberlitos / lamproitos; abertura do Atlântico Sul; fragmentação do Cratão do Congo; evolução da Bacia do Congo; Grupo do Kwango; Grupo do Kalahari; depósitos quaternários; reservas diamantíferas.

Resumo: No presente estudo, apresenta-se uma síntese da geologia da Lunda (NE de Angola) com vista a um melhor entendimento das ocorrências de jazigos primários e secundários de diamante. As enormes potencialidades diamantíferas da região são encaradas de forma abrangente, apoiadas em primeiro grau na definição do Cratão do Congo, a partir de um núcleo do Arcaico, até aos vários cinturões móveis acretados, sucessivamente, a este núcleo. No conjunto, dão corpo ao edifício cratónico onde a variação do gradiente geotérmico e a curva de estabilidade do diamante são determinantes na génese e transporte até à superfície deste precioso mineral.

Giza-se de seguida a evolução da Bacia Central do Congo, grande região situada na zona central de África onde, mercê de drenagem endorreica, se acumulam espessas sequências sedimentares, iniciadas no Paleozóico superior, e que assumem expressão máxima no Meso-Cenozóico. Também se faz referência à deformação pré-atlântica do Cratão do Congo que comanda os processos sedimentológicos, essencialmente terrígenos e continentais, deformação essa que atinge pontos críticos com a abertura do Atlântico Sul. Referem-se as grandes repercussões do "rift" oceânico no interior do cratão, reactivando estruturas tectónicas herdadas de ciclos anteriores com direcções dominantes que controlam, em absoluto, as vindas kimberlíticas e estruturas alcalinas associadas.

Dedica-se ainda um largo espaço às unidades sedimentares portadoras de diamante, com especial destaque para a Formação Calonda do Grupo Kwango, Grupo Kalahari e depósitos eluvio-aluviais do Quaternário que, em fases sucessivas, colectam e redistribuem o diamante. Discute-se, caso a caso, o potencial destas unidades na inventariação e prospecção de jazigos secundários detríticos.

A finalizar, faz-se o balanço crítico e alvitram-se as consequências económicas que impendem sobre os jazigos de diamante de Angola, primários e secundários, nas vertentes da sua potencialidade e perspectivas para o futuro.

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INTRODUCTION

Lunda Province, in NE Angola, is known as a diamondiferous region since the beginning of the XX century. Despite the fact that this region is extremely rich in diamondiferous gravels and in mineralised kimberlites, the diamond mineralisation practically extends to the entire area of Angola. However the Lunda geology encompasses all kinds of diamond ores and thus, its knowledge is very important in exploration programmes.

Taking this into account, this work deals mainly with the geology of the Lunda area. However, it is also necessary to focus on some aspects of the general geology of Angola, namely the Congo Craton evolution and some continental sedimentary units pre and post-kimberlite emplacement, that are important to the overall comprehension of the diamond problem in Angola.

The diamond exploration in the Lunda province is reported to have started in 1912 with the finding of 7 diamonds in the Mussalala River, an eastern margin tributary of the Chiumbe River. With the adequate technical support, diamond exploration began in 1913, which resulted in the opening of the first open cast mines in 1919 – Cavuco, Camimanga, Cassanguidi and Luaco mines. Since then until the year of 1999, about $63{,}6 \times 10^6$ carats were produced, in addition to the estimated 9×10^6 carats illegally exploited between the years 1984-1999. The ongoing exploitation works are conducted both in kimberlites and in eluvio-aluvial gravels.

In the past, the main exploitation activities were developed essentially in alluvial deposits, either in recent alluvial gravels related with the present drainage system, or in other sedimentary units which post-date the kimberlite intrusions. The most significant is the Calonda Formation, a Cretaceous continental unit considered as the first sedimentary collector of diamonds after the supergenic destruction of the kimberlites. The sedimentary diamondiferous deposits that are linked to the present river system drainage activity are associated with the erosion of the Calonda Formation basal conglomerates.

The continual depletion of reserves in recent alluvial gravels rich in diamonds demands that new efforts be placed on diamond exploration, which in spite of current smuggling, new findings are possible. However, the future main target in alluvial exploration and mining should be the Calonda Formation basal gravel, even with the inconvenience of the high overburden thickness that reaches frequently 50 to 80 meters or more.

Regarding the primary diamond sources, several hundred kimberlite bodies are known in Angola. Less than 50 % of these kimberlites were studied and, from these, less than 5 % are economically exploitable. Among these bodies, there are three that are in the 10 biggest diatremes in the world. In the past, only the upper yellow ground levels were exploited and a large amount of proven reserves are still unexploitable. Recently, new findings of kimberlites in Lunda have been reported. In the present state of knowledge the diamond reserves in primary sources still unknown, but a huge potential is devised in view of the alluvial ore grades.

Because of this, there is a growing interest in the primary diamond sources and some contracts have been established with international companies for exploration and mining of primary sources.

The prolonged mining history of Lunda diamonds, the data relative to past and present mining activities, the vast areas with huge mining potential both for primary or secondary diamond deposits, and the end of civil war with progressive stabilization of social and political life in the country justifies the renewed interest for diamond exploration in Angola, and consequently in the geology of the Lunda Province. Table 1 shows a synopsis of Lunda geology, with the geological units grouped considering the main tectonic cycles recognised in Angola.

The Congo Craton

The occurrence of a Precambrian cratons, especially those of Archaean age, have long been recognised as a major guideline for the exploration of primary diamond deposits – Clifford's rule (*e. g.* Clifford, 1966; Jennings, 1995 and references therein). This empirical rule has been explained with the geological conditions for the preservation of diamonds, which occur dominantly under these Archaean cratons, until a volcanic episode brings them to the surface (*e. g.* Helmstaed & Gurney, 1995).

The influence of the geological nature of the cratonic basement, in the location of the kimberlites, is paradigmatic in the case of Angola. It is notorious the dominance of kimberlite occurrences in Archaean terranes that are characterized by amphibolites, amphibolitic gneisses, mafic granulites and charnockites. The kimberlite provinces, defined by Reis (1972), are coincident with the zone of influence of the Archaean tectonometamorphic

TABLE 1

Tectonic events and lithostratigraphic units in Lunda Province (NE Angola)

CHRONO-STRATIGRAPHY		LITHOSTRATIGRAPHY	TECTONICS
	PLIOCENE	**KALAHARI GROUP** Ochre Sands and Clays Fm	EROSION
	EOCENE - MIOCENE	Grés Polimorfos Fm	EROSION-HIATUS EROSION-HIATUS
CRETACEOUS	*CENOMANIAN*	**KWANGO GROUP** Calonda Fm: Arenites and silcretes; mudstones; conglomerate intercalations; Arenites and arkoses of different colours; reddish muddy arenites; Coarse basal conglomerate.	
	ALBIAN		EROSION KIMBERLITIC EMPLACEMENT CONTINENTAL RIFTING
	APTIAN	**CONTINENTAL INTERCALAR GROUP** Mudstones and arenites with conglomerate intercalations; White and reddish sandstones (arkosic with kaolinization); Brown mudstones intercalations; Mudstones and sandstones; fine-grained conglomerate intercalations.	W-E EXTENSION TECTONICS EROSION-HIATUS
JURASSIC		**KARROO SUPERGROUP** Continental tholeiites	
TRIASSIC		**CASSANGE GROUP** Beds with *Phyllopodia* Fm Beds with Plant Fossils Fm Beds with Fish Fossils Fm	NNE-SSW FRACTURING TECTONICS
PERMIAN		**LUTÔE GROUP** Fluvio-Glacial Conglomerate Fm	NNW-SSE FRACTURING TECTONICS
CARBONIFEROUS		Muddy-Psammitic Fm Yellow Mudstone Fm Violet Sandstone Fm Tillite Fm	W-E EXTENSION TECTONICS EROSION-HIATUS
		Hyper-alkaline granites of Lunda Basic rocks of Lunda	WSW-ENE FRACTURING TECTONICS
CAMBRIAN		**WEST CONGO GROUP**	***PAN-AFRICAN OROGENY***
NEOPROTEROZOIC		Luana Fm: Quartzites and red phyllites; Brown quartzites; Conglomerates. Cartuchi-Camaungo Fm Meta-arkoses and phyllites; Meta-greywackes, quartzites; Conglomerates.	
PALEO-PROTEROZOIC		**METAMORPHIC UPPER GROUP ≈ (LULUA GROUP)** Superior Unit: silicified meta-limestones; phyllites and quartz-phyllites; phyllites and meta-sandstones with conglomerate intercalations. Inferior Unit: coloured schists and phyllites; fine-grained quartzites; black-shales, quartz-feldspathic schists, amphibolitic schists and gneisses. Porphyry granites of Lunda **METAMORFPHIC LOWER GROUP / LÓVUA GROUP ≈ (LUIZA G.)** Mica schists, quartzites and itabirites; Amphibolites, gneisses and gneissic granites.	***EBURNEAN / UBENDIAN OROGENY***
ARCHEAN		**BASAL COMPLEX** (undifferentiated) > 2.7 Ga **≈ (DIBAYA GROUP)** Gneisses, migmatites and gneissic granitoids. **CHARNOCKITIC COMPLEX** Charnockites; Quartzites; Amphibolitic gneisses, amphibolites and meta-gabros.	***LIMPOPO-LIBERIAN OROGENY(?)***

cycle (Fig. 1), despite the fact that the outcropping of the Archaean is very discontinued due to granitoid intrusions in latter orogenic cycles, mainly in the Eburnean.

The nature of the Archaean crust, composed by metasedimentary rocks with a great abundance of mafic rocks, later metamorphosed to granulitic facies, shows great mantle activity. The Eburnean crust, on the contrary, composed by gneisses, migmatites and large scale granites, is mainly acid, due to the fusion of the aluminous metasediments and little recycling of previously formed crust. The granitoid domain of this Eburnean crust seems to reveal incompatibility with kimberlite emplacement.

With this in mind, a description is made about the main tectono-stratigraphic units that constitute the craton and the corresponding orogenic events, with the aim of dissociating the cratonic core from the various fragments, successively accreted through Precambrian times.

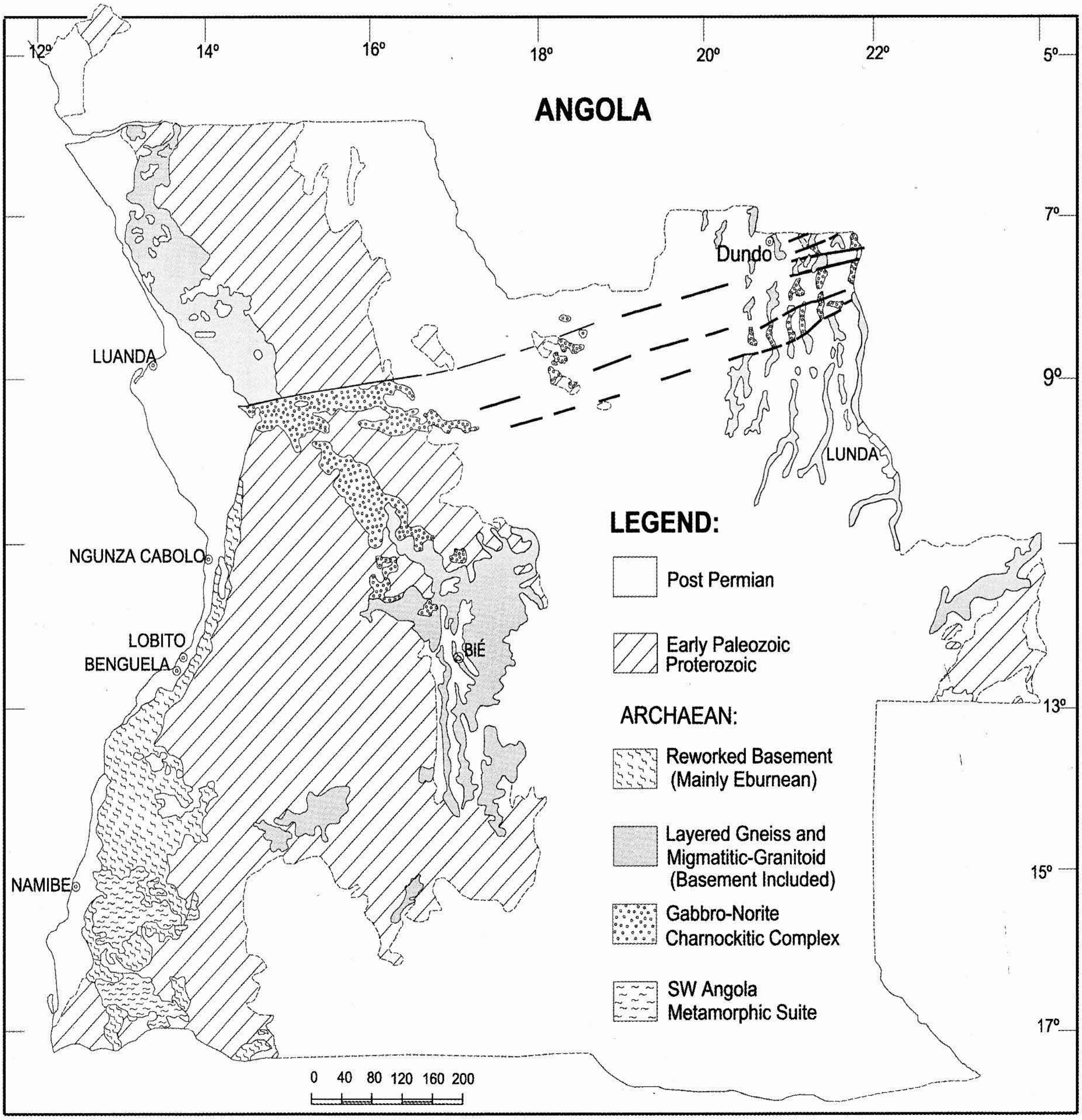

Fig. 1 – Precambrian basement of Angola – Geological Sketch Map. Adapted after International Geological Map of Africa, 1:5000 000 scale, (UNESCO, 1986); CARVALHO (1983); ARAÚJO & GUIMARÃES (1992).

This distinction is of particular importance, because the relation between the geothermal gradient and the diamond equilibrium curve defines stability zones for this mineral under the cratonic cores and instability zones under the mobile belts (HAGGERTY, 1986).

Archean cratonic nucleus

The diamondiferous area of Lunda is situated in the Congo Craton, which comprises an Archaean mafic charnockitic complex. Around this Archaean core several gneissic-migmatitic series and Palaeoproterozoic granitoids were accreted whereas Meso- or Neoproterozoic metasedimentary belts were disposed around the external limits of the Congo Craton.

The oldest isotopic data (Rb/Sr and U/Pb) indicates an age between 2.9 – 2.85 Ga for the charnockitisation of the mafic complex (norites, tonalites and amphibolites) (DELHAL & LEDENT, 1971; DELHAL *et al.*, 1976). In general, this complex is composed of acid and mafic granulites, quartzites, amphibolitic gneisses and amphibolites.

Near the border with the Congo Democratic Republic a suite of gneisses, migmatites and granitoids crops out along the valleys of Chicapa and Luachimo and are included in the so called Dibaya Group of the Kassai region (Congo), and associated with the mafic charnockitic complex. Here, the U/Pb concordia, obtained from zircons and titanites, suggest an age of 2.65 Ga (DELHAL *et al.*, 1975).

In addition to the mafic charnokitic complex and the Dibaya rocks, some authors (MONFORTE, 1988) consider the existence, in the Lunda area, of an older Basal Complex composed of amphibolitic schists, gneisses, migmatites and granitoids, which is not, in our opinion, separate from the Dibaya Group in terms of its lithology, metamorphism and structure. In fact, in the referred units, the foliation has a NE-SW to ENE-WSW direction and is affected by various deformational phases with hinge folds oriented NW-SE and NNE-SSW, probably due to superposition of later orogenic cycles. Therefore, the ages of the basic magmatism and the original crust of the Basal Complex and/or the Dibaya Group may be older, but that crust was certainly regenerated, structured and metamorphosed in a large period of time (2.9 ± 0.2 Ga). The metamorphism is amphibolitic or granulitic facies with the presence of acid granulites (charnockites) and gneissic intermediate-basic rocks (tonalites and norites) that can be explained by a process analogous to the formation of the present-day magmatic arcs and subsequent mechanisms of subduction / A-type collision (KRÖNER, 1981; 1983).

The various mobile belts, Luizian-Ubendian (Eburnean), Kibarian and Pan-African that are successively accreted to the Congo cratonic core have a weak expression in the Lunda region. However, they are worth considering, due to the fact that some of the structures that preserve the metasedimentary sequences representative of those tectonic events correspond to grabens whose faulted limits control the kimberlite emplacement.

Eburnean-Ubendian Cycle

The behaviour of the Archaean crust, present in Lunda and other zones of the centre and west of Angola, relative to the development of the successive orogenic cycles (CARVALHO & ALVES, 1993) is further analysed.

During the period of Archaean-Proterozoic transition it suffers extension, mantle pounding, rupture and, in some cases, intrusion of mafic-ultramafic masses, for example, the gabbro-anorthositic complex of SW Angola with a N-S direction along an extension of more than 200 km, and, certainly, some of the mafic intrusions of Lunda. These great mantle masses induce partial fusion of the Archaean crust and formation of granitoids and granodioritic porphyries that, in the western part of Angola, clearly marks the fragmentation of that same crust. In the Lunda sector, that fragmentation has a WSW-ENE general orientation and gives way to important subsiding zones, where sedimentary, generally siliciclastic, sequences accumulate, and are now outcropping as medium to high-grade metamorphic rocks accreted to the Archaean nucleus during the Eburnean-Ubendian orogeny. In Lunda, these are divided, from the base upwards in the Lower Metamorphic Group (Lóvua/Luiza Group) and the Upper Metamorphic Group (Lulua Group):

The Lóvua Group, equivalent to the Luiza Group of Kassai, is also present in Mufo, Luembe River, in the prolongation of the Kassai Group (Delhal and Ledent, 1973; André, 1993). It is composed of a thick sequence of quartzites, itabirites, micaceous schists and, in some places, amphibolites and gneisses. The Rb/Sr metamorphism age of these sequences is *ca.* 2.2 ± 0.1 Ga (DELHAL & LEDENT, 1973).

Also in Congo, close to the NE Angola border, a graben with the same WSW-ENE fracture direction, separated from the Dibaya Group by the Malafudi fault, preserves a low-grade metasedimentary sequence, named the Lulua Group. It is composed of schists, quartzites and basic volcanic rocks (continental tholeiites) considered as Kibarian (Delhal & Legrand, 1957; Fieremans, 1958; 1986) and always considered connected to the metasediments that occur in the Luembe River, in Angola (Andrade, 1953a; Monforte, 1988). However, the Rb/Sr dating of the metamorphism affecting the basic volcanic rocks yielded an age of 1901 ± 41 Ma (André, 1993). This author admits that the deposition of the low-grade metasedimentary sequence may express, locally, the global extensive phase that displaced the Archaean lithospheric plates and permitted the confined deposition of the metasedimentary sequences here analysed. Concluding, these sequences, affected by successive tectono-metamorphic episodes, are designated generically in Angola as the Lower Metamorphic Group of Lunda, and distinguished from the Basal Complex. They may be the expression, in the interior of the Congo Craton, of the tectono-metamorphic episode, accompanied by intense granitization, that developed to the west of the craton and, also, in the surroundings of the Tanzania Craton, being the equivalent to the more vast Ubendian-Eburnean cycle (2.0 ± 0.2 Ga). The syn-tectonic porphyritic granites of Lunda may belong to the same cycle.

In the Cambulo-Cassanguidi region, on both margins of the Luembe River, outcrops the most complete sequence of the Upper Metamorphic Group of Lunda (Carvalho, 1984), previously named "Metamorphic Series of NE Angola" (Rodrigues & Pereira, 1973; Monforte, 1988). The present group includes two series, a lower and an upper, each of which consists of three formations. Thus, the lower series consists of: A1a – gneisses and amphibolitic schists, quartz-feldspathic schists and phyllites, carbonaceous schists and phyllites; A1b – fine-grained quartzites; A1c – purple, red or grey schists and phyllites. The upper series is discordant over the lower series and consists of: A2a – phyllites and sandy schists with intercalations of conglomerates; A2b – phyllites, talc-schists and quartz-phyllites; A2c – local silicified limestones. These rocks were folded and schistosed in a main deformational event with NE-SW to NNE-SSW direction, although later fragile folding and kinks with NNW-SSE and WNW-ESE directions are observable.

From the earlier works on Lunda (Andrade, 1953a; Monforte, 1960) resulted a tendency to associate the Upper Metamorphic Group of Lunda to the Kibarian cycle, designating it "Kibaras System". Geological mapping by Rodrigues & Pereira (1973) raised suspicion that there were two distinct groups, the lowest being the oldest. On the other hand, the classical works, although including the sequence in the Kibarian cycle, always matched it to the Lulua Group (Polinard, 1934; Fieremans, 1958; Delhal, 1973), that is now considered older than previously admitted (André, 1993). In the same sequence, basic (doleritic and gabbro-dioritic) intrusions with K/Ar isotopic ages of 1320 ± 36 Ma and 1490 ± 40 Ma (Carvalho *et al.*, 1983) strengthen this hypothesis. According to these authors, these ages may correspond to an Ar loss during the Kibarian cycle and the rocks would therefore correspond to the Eburnean (Cahen *et al.*, 1984).

Pan-African Cycle

Regarding the sedimentogenesis of the Pan-African cycle (Kröner & Correia, 1980; Black, 1984; Porada, 1989), in Lunda there are only the outcrops of the Saurimo region, on the Chicapa River, to the south; the ensemble Luangando-Luana, on the Luachimo and Luana rivers; and those of the Cassanguidi region, on the Cartuchi-Camaungo streams, tributaries of the Luembe River, to the north. They allowed to define: the Luana Formation, composed of conglomerates, salmon-coloured quartzites, immature red sandstones, phyllites and red or black schists; and the Cartuchi-Camaungo Formation, also consisting from the base to top of conglomerates, greywackes, quartzites, ferruginous feldspathic sandstones and schists with purple colour. Both units are perfectly equivalent to each other, exhibit low-grade metamorphism and preserve primary structures such as graded bedding and cross-stratification, which indicate shallow platform deposition. They were preserved in extensive grabens with WSW-ENE general orientation and, more rarely, NE-SW orientation. The deformation is insignificant without the development of schistosity that only becomes penetrative in the pelitic layers.

Based on the analysis of the lithostratigraphic sequence, these units may be considered equivalent to the Xisto-Gresoso Group of the W Congo Super-Group (Schermerhorn, 1981). The age of the Luana Formation was temporarily considered by Andrade (1953a) as post-"Metamorphic Series of NE Angola" and pre-Karroo, concerning the fact that the clasts present in the Luana conglomerate revealed fine-grained quartzites, typical of those series, and also, due to the fact that the Lower Karroo tillite (Lutôe Group) contains fragments of quartzites and schists of the Luana Formation.

Congo Basin

Pre-Atlantic evolution

The Congo Basin (VEATCH, 1935) has its origin in Gondwana's interior. This basin is surrounded by the Francevillien, Sembien, Liki-Bembe and Urundi-Kibarien mobile belts from the Kibarian orogenic cycle (1.2 ± 0.2 Ga), and by the West Congolian, Oubangui-Lindien, Bushimaien and Katangien mobile belts from the Pan-African orogenic cycle (850 – 450 Ma). Posterior to the last deformational phase of this latter cycle, the basin admits little deposition in the middle Ordovician with a sandy marine transgressive sequence overlain by pelagic mud sediments and, at the top, by arkoses (Banalia Arkoses) that prograde in the basin from the E and W. The age of these arkosic sandstones is essentially Silurian-Devonian (DALY *et al.*, 1992).

Since this period, the depositional situation changed remarkably and the Congo Basin becomes a strongly subsiding area, due to the large-scale extensive tectonics, induced by distant continental collisions, such as the collision of Laurentia-Baltica with Gondwana in the Devonian-Carboniferous and the collision of Patagonia with the Gondwana in the Triassic. The completely continental sedimentological evolution and the endorheic drainage originated a thick sedimentary sequence, which in some sections attained approximately 9 km in thickness (DALY *et al.*, 1992).

During the Carboniferous and Permian the cratonic basement was covered by the continental terrigenous sequences of the Karroo and Continental Intercalar Group. In the particular case of Angola, and in the diamondiferous area of the Lunda province, it is possible to find some fragments of a glacio-fluvial and lacustrine-deltaic sequences, correlated with the Karroo (LEPERSONNE, 1951), preserved in tectonic fault-bounded structures (Table 2). This

TABLE 2

Lithostratigraphic units of the Karroo Supergroup (NE of Angola)

AGE	GROUP	FORMATION		SEDIMENTOLOGY and TECTONICS
		ANGOLA: (Mouta, 1954)	*LUNDA: (Real, 1959)*	
JURASIC		Continental tholeiitic magmatism and volcanism	Continental tholeiitic magmatism and volcanism	*Volcanism* *Hypabyssal magmatism* W-E extension tectonics
	CASSANGE	6- Beds with *Phyllopodia*	8- Muddy Sandy Complex (white and red) with: *Esteriella cassambensis* Teix. *Palaeolimnadiopsis reali* Teix.	ENE-WSW Fracturing
TRIASSIC		5- Beds with Plant Fossils		*DELTAIC* (Epicontinental)
			7- Marly and muddy shales with fossils (fishes, insects and *Estheria*)	*LACUSTRINE* (Post-Glacial)
PERMIAN		4- Beds with Fish Fossils	6- Muddy sandstones with: *Estheria anchietai* Teix.	Compressive Tectonics (?) NNW-SSE Fracturing
	LUTÔE		5- Fluvio-Glacial Conglomerate	*GLACIO-FLUVIAL* (Dark clays with dolomite and gypsum)
CARBONIFEROUS		3- Black Shales (Lunda)	4- Muddy Sandstone	
		2- Inferior Sandstone	3- Yellow Mudstones: Sandy shales and yellow mudstones with plant fossils	*GLACIO-LACUSTRINE*
			2- Violet Sandstone: Sandstone with conglomerate levels; Violet Muddy sandstones	
		1- Basal Conglomerate TILLITE	1- TILLITE	*MORAINE*

sequence ends with hypabissal and volcanic episodes of continental tholeiites. In the places without volcanism, a new fluvio-lacustrine sequence appears, which was named, in Angola, the Continental Intercalar Group.

This lithostratigraphic unit was informally defined by Diamang geologists (Monforte, 1960; 1988), comprising terrigenous deposits, bounded by a tectonic unconformity with the underlying Karroo Supergroup, preserved in graben structures, and with the overlying Kwango Group. Previously, the Continental Intercalar Group (Table 3) was considered as pertaining to Karroo, as upper Cassange or mismatched with the so called "Lunda Stage" (Andrade, 1953b). The important work made by Real (1959) gave a decisive contribution to the knowledge of those continental units and, particularly, to the definition of the angolan Karroo deposits. In the established lithostratigraphic column, he does not include, however, any sequence that may be correlated to the old Lualaba Series (old designation for the set of Stanleyville and Loia Groups).

In the Congo Democratic Republic (former Zaire), drilling works allow the definition of the *Stanleyville, Loia and Bokungu Groups* (Cahen *et al.*, 1960; Cahen, 1981; 1983). Later, Daly *et al.* (1991) proposed the stratigraphic rank of Formation to those units, with the maintenance of the unit names (Table 3). In the Kassai region, the Loia Group overlies the Stanleyville Group by a very low angle unconformity. The Bokungu Group overlies both by an unconformity (Cahen, 1983). The chronostratigraphy of those units are based on *Phyllopodes* biozones, which allow the redefinition of the Lualaba Series.

We think that, in Angola, many of the continental terrigenous deposits included in the Cassange III (Mouta, 1954) or included in the "*Camadas com Filópodes*" of several authors that have worked in the Cassange or Lunda regions, could and must be revised, similarly to what happened in the Congo Central Basin. There is a lack of detailed stratigraphic and biostratigraphic work, refinement of tectonic interpretation and, finally, formal definition of stratigraphic units.

The Continental Intercalar Group outcrops in extensive areas of the Cassange region. In Lunda, it can also be seen in several localities along the Chicapa, Luachimo and Lóvua Rivers, ranging several tens of meters (Real,

TABLE 3

Continental terrigenous units of Congo Basin (Pos-Karroo and Pre-Kalahari)

AGE		**GROUP**			**SEDIMENTOLOGY and TECTONICS**
		CONGO DEMOCRATIC REPUBLIC	***ANGOLA (Baixa de Cassange)***	***ANGOLA (Lunda)***	
CRETACEOUS	***CENOMANIAN***	KWANGO	KWANGO (CALONDA Fm)	KWANGO (CALONDA Fm)	*FLUVIO-LACUSTRINE* *TORRENTIAL*
	UPPER ALBIAN	BOKUNGU			**KIMBERLITIC INTRUSIONS** UNCONFORMITY
	LOWER ALBIAN ***APTIAN***	LOIA	CONTINENTAL INTERCALAR	CONTINENTAL INTERCALAR	*FLUVIO-LACUSTRINE* REGIONAL HIATUS
JURASSIC	***MALM***	STANLEYVILLE	CASSANGE UNDIFERENTIATED		*LACUSTRINE* W-E EXTENSION

1959; Monforte, 1988). Despite the referred ambiguity, the units sequence, observable on the left margin of the Cassamba River – east margin tributary of Chicapa River near Calonda village – are, from base to top (Pereira *et al.*, 2000b) (Table 3):

- Sandy mudstones with conglomerates, breccias and red claystones with alternating layers of whitish and reddish sandstones (≈ 10 m);
- White kaolinised arkoses and red sandstones with levels of brown mudstones (≈ 6 m);
- Reddish clays and sands with microconglomeratic intercalations (≈ 4 m).

These sequences and the respective basement were strongly segmented by extensive tectonics, coeval with the opening of the South Atlantic. Several fault-bounded structures (grabens and semi-grabens) trending mostly WSW-ENE and NNW-SSE were originated, which preserve the pre-Cretaceous sediments. These structural alignments, mostly inferred from the occurrence of the Karroo and Continental Intercalar deposits, have extreme importance for they favour kimberlite emplacement and, consequently, are excellent guides for kimberlite exploration.

Several of these and other main structural lineaments and structures correspond to inherited structures from previous tectonic episodes.

Congo Craton pre-Atlantic deformation

Inevitably, the Congo Craton exhibits the main structural trends that characterized the orogenic cycles referred to before: WSW-ENE directions from the Archaean; NW-SE trend from the Eburnean structures and N-S to NNW-SSE directions from the Pan-African cycle. These are the directions of the tectonic flow, which imply specific tension fields for each cycle that will not be mentioned here. Due to the rigid rheology of the main cratonized blocks intervening in the Pan-African cycle, the fragile structures of this cycle play an important role in the fragmentation of the Congo Craton. It will be reactivated in the tectonic episodes acting over the Gondwana, after Cambrian times, which culminate with the opening of the south Atlantic. Amongst these episodes it is worth emphasizing the continental collisions that occurred in the Devonian-Carboniferous and in the Triassic.

The main inherited structures and fractures (Coward & Daly, 1984) are represented in Fig. 2. It is with the analyses of the reactivation of the fractures that the control of the kimberlite emplacement is made.

i) – Inherited structures

The oldest structures and, certainly, those of major importance in the structural control of kimberlite diamond sources, and consequently in the distribution of secondary deposits, are those that define the WSW-ENE direction of the Lucapa Graben (Delville, 1961; Monforte, 1970). However, this structure is not confined to the Lunda area, and extends from the mouth of the Cuanza River, in Angola, to the Kassai, in the Congo Republic (Wasilewsky, 1950). The age of this structure is, at least, related to the Pan-African Cycle, but could be older than this, because the Charnockitic Complex and the Dybaia Group (≈ 2.9 ± 0.2 Ga) are preserved inside the Lucapa Graben. During the Pan-African, the tension field responsible for the W Congo and Damara mobile belts, implies a maximum tension orientated WSW-ENE. These forces must have produced extension movements in the Lucapa Graben, that lead to the preservation of the Charnockitic Complex and, also, the Luana / Cartuchi-Camaungo Formation.

ii) – Consequences of the Laurentia-Baltica collision with the Gondwana during the Devonian-Carboniferous

This collisional process originated the Variscan chain, essentially developed in central and west Europe, and also the Appalachian chain and the Morocco-Mauritania Atlas Mountains, evolving, respectively, the eastern part of North America and the northern part of Africa.

In present-day geography, the placement of the African Hercynian chains, with dominant W-E to ENE-WSW structural trends for the major structures, implies a maximum compression with a NNW-SSE direction. As a consequence of continental uplift, foreland basins or simple continental depressions are formed in the orogenic front. Examples of this situation are the epicontinental basins that occupy the whole northern part of Africa, namely, the Tindouf, Algeria and Taoudeni basins (Caputo & Crowell, 1985).

It is plausible that those NNW-SSE tensions could have some consequences on the Congo Basin, reactivating the inherited Pan-African structures as tensile fractures along the main faults with that direction. In fact, the occurrence of the tillites and fluvio-glacial deposits of

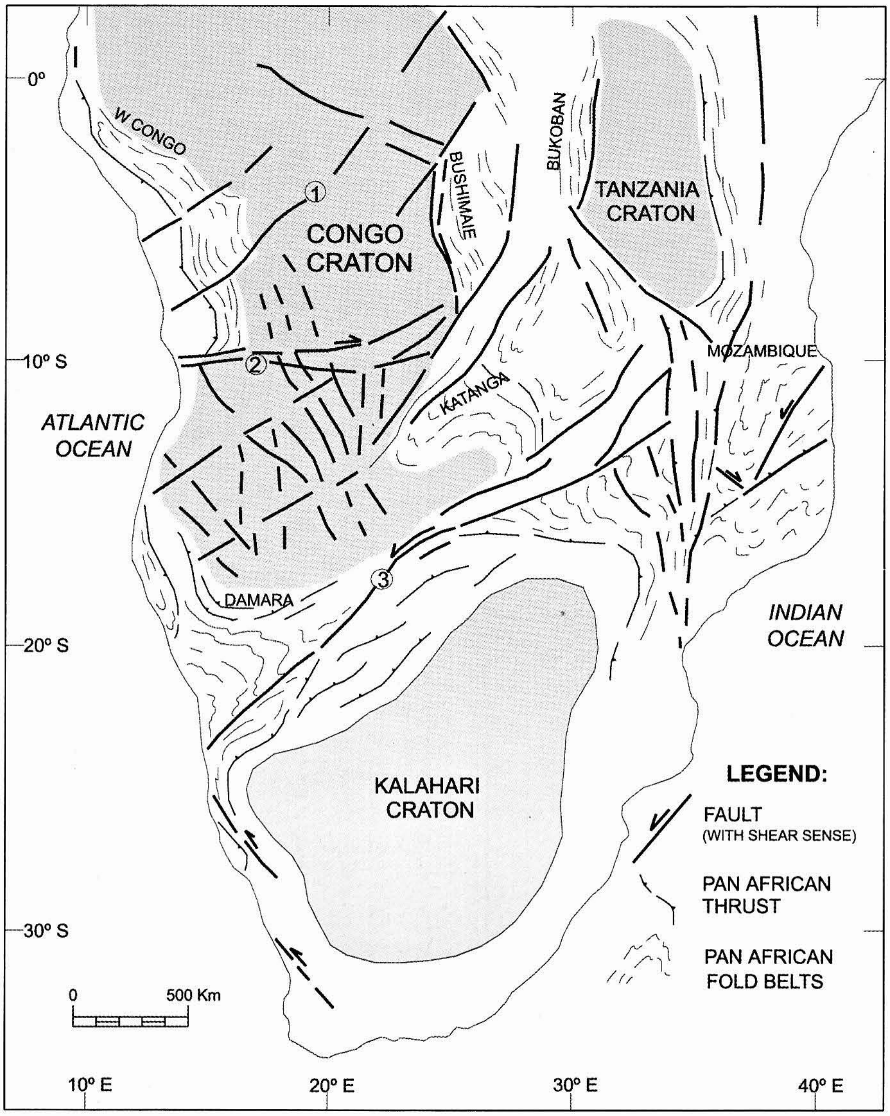

Fig. 2 – Main cratonic blocks in Southern Africa. Basement fractures: 1 – Damba structure; 2 – Cuanza-Kassai structure; 3 – Mwembeshi structure.

the Lutôe Group, outcropping along the Chicapa River in Lunda, are preserved in fault-bounded structures with NNW-SSE directions.

On the other hand, faults with NW-SE and NNE-SSE directions could be reactivated with wrench movements, while the WSW-ENE faults act as compression structures.

iii) – Consequences of the Patagonia – Gondwana collision in the Triassic

This collisional event originated the Cape Town orogen with a WNW-ESE structural trend (Daly *et al.*, 1991), and also had consequences on the Congo Basin. In fact, in the southern limit of the basin, in the Angolan territory within the basin, several structures could be seen and are perhaps more important than those formerly described (Real, 1959).

The most recent of these structures, with NNE-SSW direction and which exert a tectonic control over the Cassange Group of Permian-Triassic age, could be interpreted as tensile fractures related with the distal Patagonia-Gondwana collision.

Subordinate to the present tension field, the NNW-SSE and WSW-ENE fractures, may still be activated as wrench faults, dextral and sinistral, respectively.

The Triassic age for this reactivation followed by a reverse sense extension, near the W-E direction, preserves the Cassange Group deposits, and favours the ascent of magmatism and volcanism of the upper Karroo, and controls the Mesozoic sedimentogenesis. These structures are also fundamental for the control of kimberlite emplacement that mainly affects along the NNW-SSE and WSW-ENE conjugated directions (Monforte, 1970; Reis, 1972).

Thus, continental rifting begins in the Jurassic. The Congo Basin is under confined traction, crustal rupture and continental tholeiitic magmatism and volcanism occurs and sedimentation is interrupted. The opening of the northern Atlantic is coeval with these geological events. The continental rifting in the south Atlantic and in Angola begins in the Cretaceous, pre-Aptian (Brognon & Verrier, 1965; Pereira, 1971).

In the Albian, the opening of the south Atlantic continues and sedimentation of the Continental Intercalar Group occurs simultaneously. After the Albian, in the passive Atlantic margin, and particularly in the Cuanza Basin, alkaline and hyperalkaline intrusions and lava flows (Pereira, 1969; Pereira & Moreira, 1978) are found intercalated in the sedimentary units. These are reliably dated by post-Albian and possibly Cenomanian fossil fauna (Lapão & Galvão, 1971). In the same period, in the Congo basin, kimberlite and carbonatite volcanic activity starts, associated with the "volcanic belt of Angola" (Machado, 1959). This age is corroborated by Rb/Sr radiometric dating in several places in Angola, such as 87 ± 11 Ma, in phonolites (Silva, 1973) and 92 ± 7 Ma, in tinguaites from the carbonatite ring structure of Catanda (Silva & Pereira, 1971).

Subsequently to this period of strong tectono-volcanic and sedimentary activity at the end of the Cretaceous, followed a strong cycle of erosion during which the regional relief was eroded and the region was covered by thick sedimentary mud-sand-conglomerate sequences of the Kwango and Kalahari Groups. As a result, only the erosional activity of the present drainage pattern allows the crystalline basement, the alkaline and kimberlite volcanic structures, and also the first sedimentary collector of diamonds, the Calonda Formation, to outcrop (Table 3).

Kimberlite / Lamproite emplacement in Angola

The emplacement ages of the kimberlites in the world are well known (Kirkley *et al.*, 1992; Fipke *et al.*, 1995; Gurney, 1989; Meyer, 1985; 1987) with three Precambrian ages, a succession of Palaeozoic ages and several Meso-Cenozoic ages with a main Cretaceous period of emplacement. On the other hand, the isotopic ages obtained from diamond inclusions clearly reveal that the diamond ages are generally comprised between 3300-990 Ma. In some cases those ages are much older than the kimberlites that transport the diamond up to the surface, with ages more frequently between 100-90 Ma (Richardson *et al.*, 1984; Richardson *et al.*, 1990).

It is possible to synthesise the consequences of the difference between the ages of the diamonds and the ages of their transport to the surface: i) the diamond is originated and stored in the mantle during long periods of time; ii) it is transported to the surface in specific periods (inter-orogenic) of Earth's history; iii) diamonds of different ages occur in the same pipe, as in the case of the Finch mine (Richardson *et al.*, 1990), which implicates the existence of several mantle sources crossed by the same kimberlite during ascencion; iv) and, finally, the diamonds are not genetically related with the kimberlites, that serve only as a transportation medium up to the surface. The diamond sampling in the mantle is done by a mechanism of geothermal gradients and thermodynamic conditions for diamond stability (Kennedy & Kennedy, 1976; Haggerty, 1986).

In the distribution map of kimberlites and alkaline ring structures in Angola (Fig. 3), it is possible to see the seven kimberlite provinces that are presently known (Reis, 1972; Reis & Barros, 1981).

The four most important of those provinces are: Lunda (I); Cucumbi, Cacuilo and Cuango Rivers region (II); Cuanza Basin (III) and the Cunene, Queve and Catumbela River springs region (IV). These provinces are aligned along one NE-SW macrostructure (Lunda – Walvis Bay lineament or Volcanic Belt of Angola). The Lunda province is controlled by fault-bounded compartments with WSW-ENE direction in an echelon pattern, dislocated by NNW-SSE faults. The other three main provinces (II, III and IV) are tectonically controlled by NE-SW and NW-SE fractures.

The remaining provinces: Longa River springs (V), Cassinga region (VI) and Cubango River springs (VII), are tectonically controlled by NW-SE fractures. Together with provinces III and IV, they form a structural lineament with this same orientation.

In the crossing of these two systems of major fractures several kimberlite pipes were found using airborne

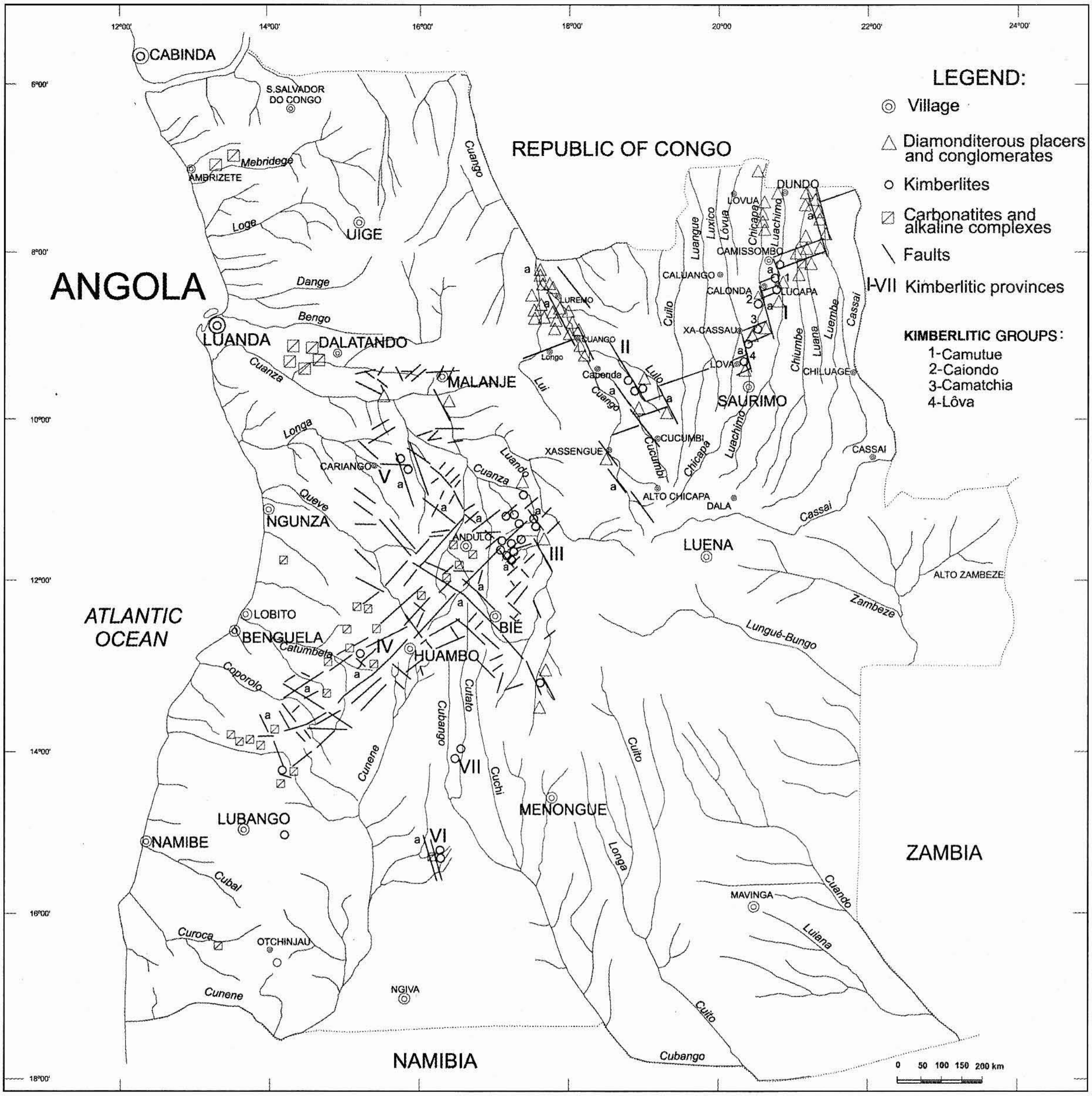

Fig. 3 – Occurrence map of kimberlites, alluvial deposits and ring alkaline structures (Kimberlitic Provinces of Angola), after (Reis, 1972).

magnetic surveys (Reis, 1971). The Atlantic traction forces cause the formation of graben-type structures that were formerly described, that control and preserve the secondary deposits of diamonds: Kwango Group, river terraces and present alluvial deposits.

From the exposed, we emphasise the strong structural control for the kimberlite emplacement. The main weakness fracture zones where the kimberlites are found were inherited from Precambrian orogens and from the tensile fracture systems actuating in the Congo craton between the Carboniferous-Permian and the Cretaceous (Pereira *et al.*, 2000a).

In Lunda, there are several petrographic facies of kimberlite: porphyritic type, breccias and tuff-breccias. The mode of occurrence of kimberlites is mainly in diatremes or pipes, but dikes and sills are also known. The pipes are elliptical or circular, irregular, with variable dimension and are generally small in size. However, the Catoca, Camafuca-Camazambo, Camutué, Camatchia-Camagico pipes form the exception in this area as these are much larger in size, uneroded and consist of groups of diatremes. Their composite nature gives them the larger dimension. The dikes and sills are thin and can attain lengths up to one hundred meters, showing a porphyritic structure and few xenoliths. Generally these are related with fracture lineaments or have a radial disposition in relation to the larger pipes, as in the case of Camutué.

As far as we know there is no isotopic data on kimberlites from Angola. The kimberlites are probably post-Paleozoic since in the Chicapa River, the Camafuca-Camazambo kimberlite, the Karroo and the Continental Intercalar deposits are cross cut by the diatreme (REAL, 1959). We therefore presume that the Lunda kimberlites and, in general, the Angolan kimberlites are emplaced in the Cretaceous period with the opening of the South Atlantic.

Further age indication comes from the relation of the kimberlite occurrences within the "Volcanic Belt of Angola", a major structure in Angolan geology, which plays an important role in the kimberlite magmatism.

The "Hotspot"/ "Thinspot" of Walvis Bay – Rio Grande do Sul, has been known for a long time as the "Volcanic Belt of Angola" (MACHADO, 1959; EDWARDS, 1971; CORREIA, 1988). The evolution of this hot spot is reflected in the strong differentiation that can be seen along the Volcanic Belt from NE to SW. In the northeastern kimberlite provinces, there are rich exploitable kimberlites in Lunda (I) and in Bakwanga (Congo Democratic Republic) (WASILEWSKY, 1950); poor kimberlites with diamond and pyrope in Cucumbi, Cacuilo and Cuango (II); kimberlites with pyrope and subordinate diamond in the Cuanza basin (III); practically sterile kimberlites in the Cunene; Queve and Catumbela River springs (IV); and, finally, concentric structures with nepheline syenites and carbonatites in the south-western part of the Lunda – Walvis Bay lineament, such as: Zenza, Nonga, Elonga, Balombo, Longojo, Bonga, Tchivira, Serra da Neve, Virulundo (LOUREIRO, 1967). These occurrences seem to confirm MILASHEV (1965) and BARDET (1973-1977) ideas. The variation in geothermal gradient from the centre to the external part of the craton and the fractionation of the alkaline magma, associated with the conditions of diamond stability with the phase transformation of diamond in graphite, is totally confirmed in space and time in Angola (Fig. 3).

There is a question related with the time of this magma evolution between the Lunda and the Namibe region (PEREIRA, 1969). An Albian age (110 Ma) is admitted for the Lunda kimberlite intrusions while the alkaline magmatism of Walvis Bay is of Cenomanian-Turonian age. If we consider an expansion rate of 10 cm/year for the South Atlantic and/or equal velocity in the NE movement of the African Plate, the distance of approximately 2000 km between Lunda and Walvis Bay is overcome in 10 Ma. These numbers point out the validity of the hypothesis of an enormous magmatic diapir in expansion that must establish the control of the diamond in Angola.

All these geological episodes are related to the opening of the Atlantic. In fact the breaking up of Pangea and the opening of the Atlantic caused intense fracturing in the African continent, with a triple joint near Lake Chad and three radial megastructures: one in the direction of Tunis, another till the Fernando Pó islands and the third, more irregular, that passes through Mombassa (Fig. 4a). This megafracturing originated three more or less cratonic megablocks: Occidental (O. B.); Arabian-Nubic (A. N. B.) and Austral (A. B.). In the Neocomian-Aptian occurred the separation between the Arabian-Nubian and Austral blocks, causing a left wrench movement in the Chad-Tunis structure; in the upper Aptian-lower Albian, by NE-SW extension, the separation between the Occidental and the Arabic-Nubian blocks occurs, implying the development of the dextral transform fault that separates the Occidental and Arabian-Nubic blocks from the Austral block (Fig. 4b) (FAIRHEAD, 1988; UNTERNEHR *et al.*, 1988; GIRAUD & MAURIN, 1991).

Since the Albian, the Atlantic opening process induces intensive W-E tensile activity in the Austral crustal block (MARTIN, 1973; OJEDA, 1982; REYRE, 1984), which, in turn, is also divided in at least three other crustal cratonic blocks: Congo, Tanzania and Kalahari (Fig. 2). The Congo and Tanzania cratonic blocks are also separated from the Kalahari craton by the Mwembeshi left transform fault, particularly active in Pan-African times and responsible for the formation of the Damara belt (KRÖNER, 1982), and the Lufilian Arc (COWARD & DALY, 1984). The tensile forces reactivate weakness zones inherited from the Precambrian orogenic cycles and from the continental collisions with Gondwana, formerly referred.

Concerning the Congo craton, and in the specific case of Angola, the main weakness zones defined are: WSW-ENE, NW-SE and NNE-SSW. Under the W-E tensile forces, coeval with the Atlantic opening, the WSW-ENE fractures will react mainly with wrench movements, while the other become mainly tensile.

Considering all these facts and models it is worth emphasising some ideas about the most successful methods

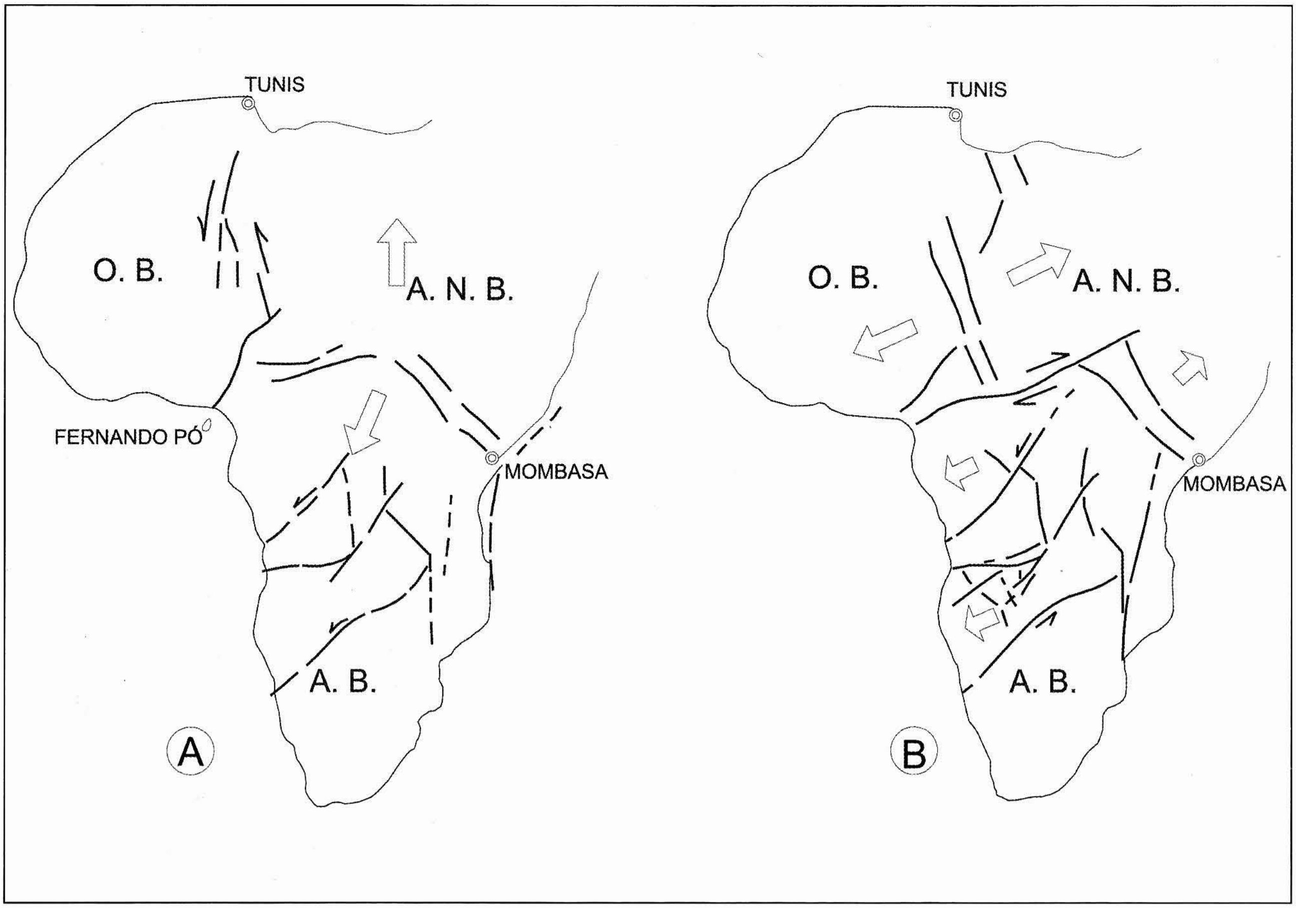

Fig. 4 – Rift episodes and fractures reactivated in the cratonic basement of the African continent during the lower Cretaceous. Adapted after FAIRHEAD (1988) and UNTERNEHR *et al.* (1988): a) Neocomian-lower Aptian; b) Upper Aptian-lower Albian.

of primary diamond source exploration in Lunda. In view of the previous ideas and assumptions on the major geological controls of kimberlite emplacement, the most favourable areas are those that have a cratonic basement, and alkaline volcanism associated with deep transcurrent or extensive tectonics. In Lunda, very thick post-kimberlite terrigenous sediments, deep weathering profiles and dense vegetal cover obscure these geological conditions. This inevitably leads to choosing geophysical methods of kimberlite exploration over other conventional methods.

Importance of airborne magnetic surveys

This method of exploration revealed itself very useful in the location of the major lineaments that control the ascent and emplacement of kimberlites. Thus, this method was decisive to the discovery of volcanic alkaline structures where those rocks are found. In fact, the crystalline complexes have, throughout geological time, been subjected to different diastrophic phases that have modified the physical properties of the various lithological units. These changes have been brought out by metasomatic phenomena and magmatic differentiation process (REIS, 1966). On the other hand, the basic and ultrabasic complexes, as shown by their circular alkaline-carbonatite structures, have had a history of tectonic control along the main lines of structural weakness, together with magmatic differentiation (REIS, 1971; REIS & BARROS, 1981; REIS & MONFORTE, 1981).

The main suite of volcanic rocks consist predominantly of andesitic laves, rhyolites and gabbros which are related to the alkaline complexes and the nepheline syenites, ijolites, trachytes, phonolites, breccias, tuffs, carbonatites and kimberlites. The carbonatites and kimberlites associations under similar tectonic conditions has been discussed by several authors (DAWSON, 1980; BARDET, 1973; NIXON, 1987; KORNPROBST, 1984).

A good example of the aeromagnetic application for kimberlite detection is shown in Fig. 5, which gives a zoom sketch map from the Uambo region, in central Angola.

The structural map shows all the geological and geophysical data and delimits the three main WSW-ENE, NW-SE and NE-SW fault systems. Minor structures are also marked. The oldest tectonic structures are perhaps

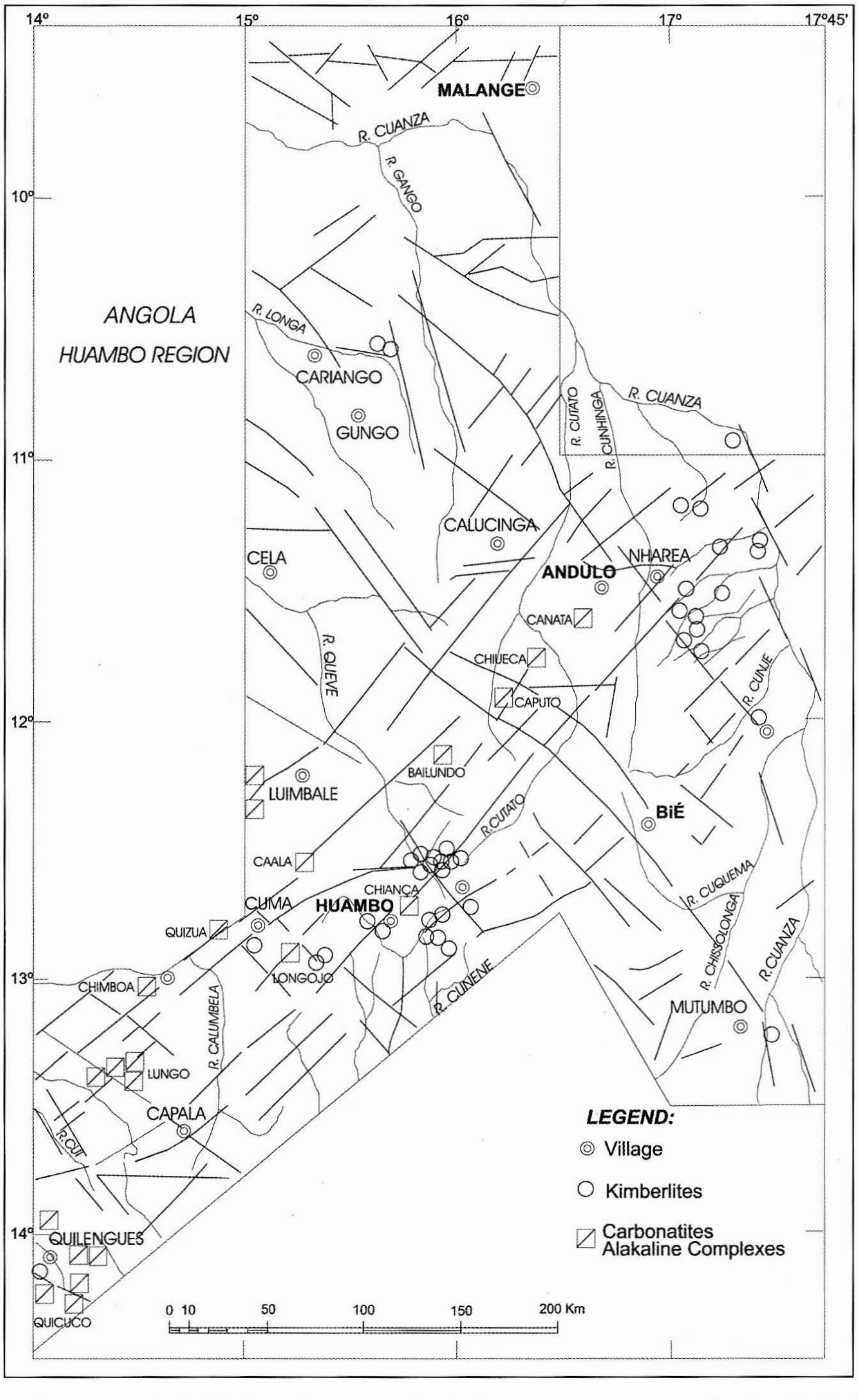

Fig. 5 – Magnetic and tectonic structures, in the Uambo region, central Angola; they establish the control of carbonatite-kimberlite occurrences, after (Reis, 1971).

the W-E ones, which were reactivated several times with WSW-ENE deflections.

The magnetic anomalies related to these structures are, generally, very elongated, parallel to subparallel, being interpreted as the reflex of deep fractures that control the ascent of explosive kimberlites and alkaline magmas. In Angola, two main structural bands of high magnetic susceptibility, magmatic permeability and close relations with the diamondiferous occurrences are put in evidence: one with NE-SW trends and approximately 1800 km in extension, from Bakwanga to Namibe, passing through Lucapa, Cacuilo, Andulo and Huambo; and the other with a NW-SE orientation and approximately 1700 km defines the alignment of the Cuango and Cuando Rivers, from the NW Angolan border to the SE border with Zambia. This latter structural and magnetic lineament is, in our opinion, the one with greater potential for the discovery of primary kimberlite sources, particularly in Cuando and in international Cuango rivers.

The interaction of both of these tectonic lineaments constitute the most likely locations for carbonatites (LOUREIRO, 1967) and kimberlite emplacement and, thus, are of great interest in the search for primary diamondiferous deposits.

Congo Basin post-kimberlite terrigenous sequence – the secondary diamond deposits of Lunda

The long-term continuous mining activities with consequent depletion of aluvial reserves, and the explosion of smuggling in the ninety's led to a renewed interest to the primary sources. Nevertheless, a huge amount of potential reserves are still available in secondary deposits, which is the reason why knowledge of the stratigraphy of the terrigenous continental deposits post-kimberlites is essential.

Coeval with alkaline magmatism, kimberlite/lamproitic and carbonatitic intrusions, a period of intense transcurrent and extensive tectonism occurred, with the filling up of large depressions. Then, a succession of erosion/sedimentation cycles follows the former tectonism and magmatism. The thick continental sequence originated comprises all the diamondiferous sedimentary units: Kwango Group, Kalahari Group and recent alluvial deposits. Thus, knowledge of this succession of geologic events is fundamental for diamond exploration in Angola (Fig. 6).

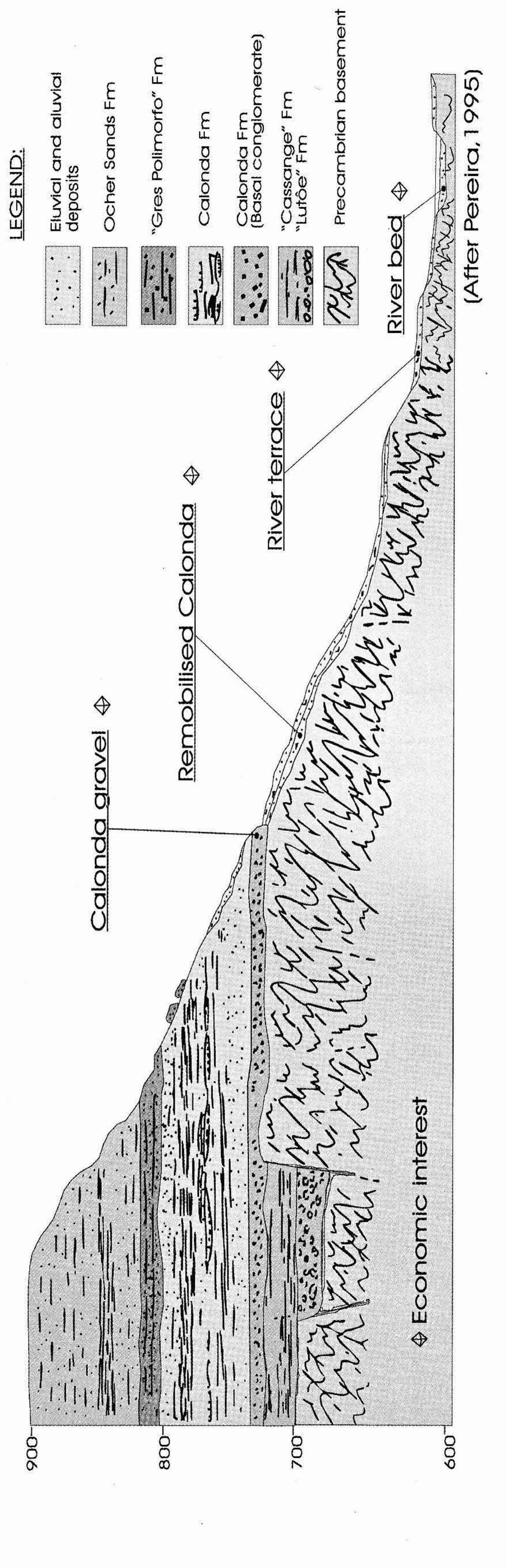

Fig. 6 – Relationship between the eluvio-alluvial diamondiferous deposits of the Lunda and the post-Pliocene morphogenesis.

Kwango Group – Calonda Formation

The Calonda Formation (CF) is considered the first sedimentary collector of diamonds, and is correlative with the continental diastrophism and supergenic destruction of kimberlite diamond sources. As a consequence, the CF collects the products of surface destruction of kimberlites and lamproites (DELVILLE, 1973; RODRIGUES, 1993).

The Calonda Fm sedimentogenesis is, thus, controlled by the filling-up of fault-bounded large depressions that originated by extensional tectonics coeval with the opening of the South Atlantic (REIS *et al.*, 2000).

The Calonda stratigraphic sequence is composed mainly of torrential deposits, correlated and proximal to the elevations, that express high energy and transport capacity in a dense and viscous medium, where angular coarse and fine clasts are transported by a dense argillaceous mass, in water suspension. It show stages of great recurrence, with conglomeratic and argillaceous intercalations, as the relief becomes less pronounced. Gradually, the sedimentogenesis gains lagoonal characteristics downstream, as a result of the grouping and coalescence of weak currents coming from lower lands.

In a mature stage of pediplanation, in the Upper Cretaceous, this type of deposit implies an abundance of regolith and a great rainfall volume, as was interpreted from the textural maturity of the arenaceous sequences and from the sedimentary structures, namely cross-bedding.

At the top of the CF sequence, the limonitic, silcrete and calcrete levels, indicates the larger frequency of dry seasons and the complete disappearance of surface waters. Generally, the sedimentological column ends with terrigenous sandy-argillaceous materials with sparse angular pebbles. These uppermost levels correspond to a low energy laminar flow transport with aeolian transport episodes.

The Calonda Formation was informally defined in Lunda (NE Angola) (ANDRADE, 1953a, b; 1954). In the Democratic Republic of Congo, together with other lithostratigraphic units, it is placed in the frame of the Congo Basin and it has been included in the Kwango Group (MONFORTE *et al.*, 1979; CAHEN, 1983), with an age considered as Cenomanian, on the basis of fish macrofossils and palynomorphs. In the latter years of the DIAMANG mining activities, several detailed studies were carried out from a lithostratigraphic and economic point of view (SARAIVA, 1973).

The Calonda Fm lithostratigraphy, with an average thickness of about 40-60 meters, is the base upwards:

- Coarse fanglomerate / conglomerate, with a sandy--clay matrix showing several different sedimentological types whose definition and classification was proposed by several authors (*e. g.* FIEREMANS, 1955; MONFORTE, 1960; SARAIVA, 1973). In most cases the basal conglomerate produces diamonds and some attempts were made in order to relate the sedimentological type of each conglomerate with its diamond content.
- Sequences of immature arenites with rare mudstone intercalations; the sandstones have cross stratification and several colours that vary from place to place: violet coloured muddy arenites; white arkosic-kaolinitic arenites and reddish limonitic arenites;
- Fine-grained conglomerate recurrences, with an argillaceous matrix;
- Argillaceous component increasing upwards with sandy-argillaceous levels with limonitic horizons, silcretes and calcretes indicating dry periods.
- Predominance of argillaceous and sandy-argillaceous levels with brownish colours at the top of the sequence. Sometimes with dispersed pebbles.

Kalahari Group

The lithostratigraphy, sedimentology and tectonics of the formations included in the Kalahari Group must be studied in the light of the global climate changes that occurred during its sedimentation. In fact, the Kalahari sedimentogenesis is coeval with the main erosive periods that have sculptured the relief, resulting in vast planes. It is the knowledge of the chronology of these planes surfaces, coeval with depositional hiatus and together with climatic changes that must be present in the study of the Kalahari Group.

The formal definition of the units of the so-called Kalahari System, was made in the Conference of Geologists of the Congo Basin in 1945 (LEPERSONNE, 1945) and completed later by CAHEN *et al.* (1946). These authors proposed three main divisions for the Kalahari, which resulted in the three formations considered until today:

- Kalahari C (supérieur) – Kalahari Sands
- Kalahari B (intermedium) – "Grés Polimorphyiques"
- Kalahari A (inférieur) – Kamina Formation

The lower Kalahari is not present in Lunda or, what seems no probable, it is confused with the top of the Calonda Formation. This lack of definition could be due to the facies similarities when the conglomerate is not present (MONFORTE, 1960).

Based on the works of several authors (POLINARD, 1948a, b; MOUTA & DARTEVELLE, 1952; JANMART, 1953; CARVALHO, 1955; GREKOFF, 1958; DE PLOEY *et al.*, 1968), it was possible to define a lithostratigraphy for the Kalahari of Lunda:

- *Upper Series or Ochre Sands Formation*, formed by gravel layers at the base with ochre sands and yellow sands at the top;
- *Lower Series or "Grés Polimorfos"* Formation, composed, from base to top, of conglomerate, purple sandstones locally silicified, chalcedony and sandy chalcedony, silicified quartzitic sandstones, silcretes (FERREIRA, 1958), and white or red friable sandstones.

An Eocene to Oligo-Miocene age has been considered for the "Grés Polimorfos" Formation based on fossil findings, namely Ostracods, Gasteropods, and oogonic fragments of *Chara* genera.

From our personal experience in NE Lunda, the transition between Calonda Fm and the Kalahari Group is made by a sedimentological unconformity with a weak erosive event:

- Wherever the contact is observable, it is moderately undulate;
- There could be several contact lithologies: in the C. F. sandstones it is possible to find mudstone levels, cross-bedding, parallel bedding and the presence of feldspar; in the "Grés Polimorfos", apart from the strong silicification, these units do not include mudstones, the feldspars are not visible in hand specimen and the bedding planes are not perceptible.
- In the basal levels of the "Grés Polimorfos", there is occasionally a well-rounded gravel made up of clasts of quartz and quartzite with angular chalcedony that contains scarce diamonds.

Post-Pliocene diamondiferous alluvial-eluvial deposits

In a study of these kinds of deposits, it is very important to consider the last planation event in the Congo Basin. This event is post the Ochre Sands Formation, partly coeval with the late Pliocene pediplanation and cuts the Miocene and the late Cretaceous peneplains. Most of the Angolan geomorphology is dominated by such planation surfaces, with a stepping succession of planation surfaces from the interior of the country to the coast. The surfaces are also present in the endorheic morphology of the Congo Basin.

The Pliocene peneplain is, thus, the best reference surface for the Quaternary eluvio-alluvial deposits, with or without diamonds. This surface covered by:

- Very dispersed plateau gravels composed by ferralite elements and clasts of "Grés Polimorfos"; these deposits express the last stage of planation once the finer elements have been removed by the wind and the surface-waters;
- Sands covering the former plateau gravels, sometimes with several meters of thickness. These sands occur between altitudes of 800-900 m, and are of aeolian origin, resulting from the redistribution of Kalahari sands in an arid climate.

The maximum altitude of the Pliocene surface marks the dividing line between the main Lunda rivers flowing northwards. This surface is cut by the sub-actual and actual river drainage, with the correspondent planation levels. Some of these planation levels are marked by terrace deposits, some of which are economically important. MONFORTE (1988), based on previous studies (POLINARD, 1949; BREUIL & JANMART, 1950; JANMART, 1953), defined these erosion cycles for the Lunda region.

As mentioned previously, humid tropical climates are favourable for intense alteration while sub-arid climates generate great masses of regolith. The quaternary climate, in the region of the Congo Basin, of low latitudes, is characterised by an alternation of these conditions. Therefore, the development of placers and residual deposits depends on the combination of tectonic movements and climatic conditions (HALL *et al.*, 1985).

Tectonism takes place in the Holocene. In fact, a tilt movement to the W, affecting a sector of the Congo Basin induced the drainage of the great African river to flow to the Atlantic. From this point on the sedimentation is definitely altered in the basin and it becomes no longer endorheic, the level base is lowered and the encasement of the great tributaries of the Congo River starts. Wide valleys with flat floors are generated and rapidly the riverbed is excavated on the friable units of the, also designated, Central African Basin.

Remobilised Calonda, Kalahari and plateau deposits

The active slope erosion, cutting the easily friable Calonda and Kalahari deposits, remobilise and deposits its materials directly over the sloping crystalline basement or in various level terraces.

Frequently, the ore grade diminishes, due to the introduction of large volumes of barren Kalahari sands and gravels. However, if the erosion is directed on the Calonda basal conglomerate, a fine deposit with rich ore grades could be formed on top of the basement. In Fig. 6, the fine layers originated economically important diamondiferous deposits.

Upper Terraces (40 to 20 m)

i) – 40 meter terraces

It contains non-rounded Kafuense industry, pre-Chelles-Acheulense (Janmart, 1946a, b). Some doubts persist about the origin of these deposits (Leakey, 1948). In fact, there is a mixture of angular and rounded clasts. These materials could be slope degradation products, the rounded materials having come from the pre-Pliocene units.

ii) – 20 meter terraces

They contain non-rounded Kafuense industry, pre-Chelles-Acheulense (Janmart, 1946a, b).

Contrary to the former terraces, relative to which doubts subsist about the deposition process, these deposits constitute layers with a thickness that could rise to three meters, and are undoubtedly deposited by rivers during their erosion activity until the present level position.

These terraces are situated approximately 20 meters above the present riverbed level, on top of the crystalline basement and they are very common in NE Angola.

Their economical value is higher than that of the 40 meter terraces.

Main rivers low-level terraces ($\leq$ 10 m)

They contain Oldwense industry and some other types of Chellense and Chelles-Acheulense industry.

Between the high terraces and the low terraces deposition, an important time span occurred, during which important climate changes happened (Monforte, 1988). These changes originated an important ferralite level named "Pleistocene Laterite I", whose genesis was favoured by the alternating succession and dominance of the hot dry season over the rainy one.

These terraces, with a thickness between 0.30 and 1.50 meters, rest on top of the crystalline basement or on top of the referred laterite.

Main rivers alluvial flat and riverbed deposits

Under this title are grouped several depositional events in several studies (*e.g.* Janmart, 1946a; Leakey, 1948; Monforte, 1988).

They are low altitude terraces, with ferralitic levels, changes in depositional regime of the river courses, terrigenous intercalations due to the emersion of the deposits, etc., essential, without doubt, to the research on climatology and lithostratigraphy of recent Quaternary (Hall *et al.*, 1985). Any work in this domain may not do without this analysis.

In a mining perspective, all of these deposits are located on the river margins, alluvial flat and on the present riverbed.

Economical situation analysis of Angolan diamondiferous deposits

The preceding text is a synthesis of the main aspects related with a complex geological problem that is the diamond deposits of Angola. We have made reference to some scientific and technical matters that must be considered in the study of the genesis and location of primary and secondary diamond sources. Below, the economical consequences of this knowledge in view of future trends and possibilities for diamond exploration and exploitation in Angola is discussed.

i) Diamondiferous potential

When Angola became an independent country, on the 11th of November of 1975, the ore reserves in diamond were considerable (65×10^6 carats), and the exploitation rate reached 2.1×10^6 carats/year. These numbers show the effectiveness of the DIAMANG mining and exploration activities until the end of its work. The succeeding Angolan Diamond Mining Company (ENDIAMA) took large benefits of this heritage to the present-day, if we take into account that no more intensive significant exploration works have been carried out since 1975. Despite some rare exceptions the present-day mining works are still based on the DIAMANG ore reserves. Today there is no information about new proven reserves and the depletion of reserves is poorly controlled because of smuggling.

In 1975 the known proved reserves are, by ore type:

- Primary sources (kimberlites/lamproites): ≈ 45 × 10^6 carats;
- Sedimentary detrital deposits (recent alluvial-eluvial gravels, and some area with Calonda Fm basal gravels): ≈ 20 × 10^6 carats.

In relation to these numbers, it is important to notice that statistical studies carried out in several tens of years have shown that the exploitation results are 22 % higher than the ones of exploration. On the other hand, an increase in 30-40 % of ore proved reserves must be considered, because in almost all the defined mining blocks the exploitation continues beyond the limits of these blocks with ore treatment plant ore grade control.

The estimation of probable diamond reserves, was in 1975:

- Primary sources (kimberlites/lamproites?): ≈ 40 × 10^6 carats;
- Sedimentary detrital deposits in recent alluvial-eluvial gravels (undervalued reserves): ≈ 7,5 × 10^6 carats;
- Calonda Fm basal gravels: ≈ 26 × 10^6 m^3 (a total of 10.4 × 10^6 carats is estimated), with an average ore grade of 0.4 ct/ m^3 and 0.8 m for the conglomerate thickness with an overburden thickness of about 30-60 m.

The Calonda Fm basal conglomerate was investigated and sampled by drilling. In face of the ubiquitous occurrence of this lithostratigraphic horizon in Lunda, it is easy to point out the huge potential of Calonda Fm as a future diamond reserve. The need for an adequate exploration program is obvious (PEREIRA, 1996; RODRIGUES *et al.*, 2000a; RODRIGUES *et al.*, 2000b).

All of the previously referred data on the diamond potential was collected and known only due to the work and experience of the DIAMANG geologists and miners in several scientific areas such as: remote sensing, geophysics, geochemistry, loaming mineralometry and also biology (botany and termites). Together, several techniques developed in these scientific areas lead to the discovery of 383 kimberlites, between 1952 and 1973 (176 in 1973). Besides these, 46 new kimberlites were found by CONDIAMA (a DE BEERS and DIAMANG associated Company), in a total of 429 identified kimberlites until July of 1973, which can be grouped in the following manner: 2.8 % economically exploitable; 1.2 % under evaluation studies; 46.6 % without diamonds and 49.4 % not studied.

At present time, a number about 600 kimberlite bodies were identified.

ii) Future perspectives

As a result of the generalised illegal miners all over the country, the secondary diamond deposits related with the actual river drainage does not represent an economic source to the country, and, in our opinion, they are in the future completely lost for any kind of organised industrial scale mining activity. In fact, since 1978 and with an ever increasing rate, since 1985 that those kinds of illegal mining activities have taken place in those kind of deposits. The consequent inexistence of effective control on high-grade / little-overburden thickness and well-sized good-quality stones lead to a “diamondiferous” chaos in Angola.

As a result of these illegal activities, the benefits for the country were none and even highly negative, due to the illegal diamond exportation to foreign international markets (Antwerp, Israel, USA, etc), but also because the diamonds serve as financial support for other activities.

A few, but important alternatives are left for the secondary deposits: i) the main river bed deposits, unexploitable without adequate technical support; ii) in relation to the referred lost reserves, an alternative could be the establishment of an official buying system, with attractive prices, that could conteract the illegal diamond exportation.

Therefore, the good use of the remaining economically viable kimberlite and Calonda Fm diamond resources that, due to their specific geological characteristics, are untouchable by illicit miners, is imperative.

In relation to the Calonda Fm, the usually thick overburden hinders the activities of illegal diamond prospectors. There are three main regions of high economical potential (REIS *et al.*, 2000): NE Lunda, Cuango drainage basin, and particularly the middle course of the Cuando River, that allows the establishment of several economical projects: i) Malúdi region (NE Angola) with recognised basal gravels approximating 22 × 10^6 m^3, with 30-60 m of overburden thickness and extremely good gem-quality diamonds; ii) Cuango River basin, between the Luremo and Cuango villages, with well-known values of mineralisation and also good quality and size of diamonds; iii) middle of the Cuando drainage basin as a potential area for the occurrence of the Calonda basal gravel, but in a state of incipient geological knowledge.

In relation to the primary sources – kimberlites and lamproites – we point out the main provinces of location (Reis, 1972), but it is possible that numerous others are yet unknown. This type of ore demands a vast and intensive exploration program aimed at initial area selection and later with refined exploration methods on a case to case basis.

Our opinion is that when the country becomes socially stabilized, enormous unknown diamondiferous resources will be revealed as a consequence of an adequate scientific and technical program in such a large area available for exploration.

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