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Multiphase origin of the Cu–Co ore deposits in the western part of the Lufilian fold-and-thrust belt, Katanga (Democratic Republic of Congo)

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Abstract

A multiphase origin of the Cu–Co ores in the western part of the Lufilian fold-and-thrust belt in Central Africa is proposed based on literature, satellite image interpretations and petrographic and fluid inclusion analyses on samples from the stratiform mineralization of Kamoto and Musonoi (DR Congo). The various mineral occurrences in the Katanga Copperbelt can be classified in distinct categories: stratiform, supergene enrichment and vein-type. The stratiform mineralization form the largest group and can be found mainly in Lower Roan (R-2) rocks, which can be identified as ridges on satellite imagery. Ore deposits outside the R-2 occur along lineaments and result often from supergene enrichment.

The main phase of the stratiform mineralization in the Katanga Copperbelt occurred during diagenesis preceding the Lufilian orogeny. Petrographic observation identified various mineralizing phases, which played a role in the formation of these stratiform mineralization. Mineralization started during early diagenesis, but mainly occurred during further burial. After the formation of early diagenetic pyrite, the circulation of diagenetic Cu–Co-rich fluids resulted in the formation of the main mineralization. Preliminary microthermometric investigation of primary inclusions in authigenic quartz, associated with the main stage of stratiform mineralization, indicates that an H_2O–NaCl fluid with a minimum temperature between 80 and 195 °C and a salinity between 8.4 and 18.4 eq. wt% NaCl circulated during the main phase of mineralization.

Numerous faults and fractures formed during the Lufilian orogeny cut the stratiform mineralization. They are, however, at Kamoto and Musonoi only associated with minor sulphides. Supergene alteration along faults and fractures resulted in an enrichment of the mineralization, with the formation of secondary Cu-oxides, -carbonates and -silicates.

The importance of the interaction of various processes for the formation of economic Cu–Co ore deposits is confirmed by the straightforward relationship on satellite imagery between the location of economic mineral occurrences and faults, which acted as pathway for descending waters that caused the supergene enrichment and upgrading of the primary mineralization.

Keywords: Stratiform Cu–Co mineralization; Copperbelt; DR Congo; Diagenesis; Satellite imagery; Supergene enrichment

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1. Introduction

The Central African Copperbelt forms one of the largest metallogenic provinces of the world (Fig. 1). It hosts Cu–Co deposits within the Neoproterozoic Katanga Supergroup of the Democratic Republic of Congo (DRC) and Zambia. The sulphide bodies are present from Kolwezi up to Kimpe in the DRC (Fig. 1). The sulphide occurrences are located in two stratigraphic levels forming the "lower" and "upper" orebody, with a total cumulative thickness varying between ~15 and 55 m (Cailteux et al., 2005). Total resources of the Copperbelt in the DRC and Zambia are estimated at more than 150 million tons of Cu and 8 million tons of Co metal (Misra, 2000).

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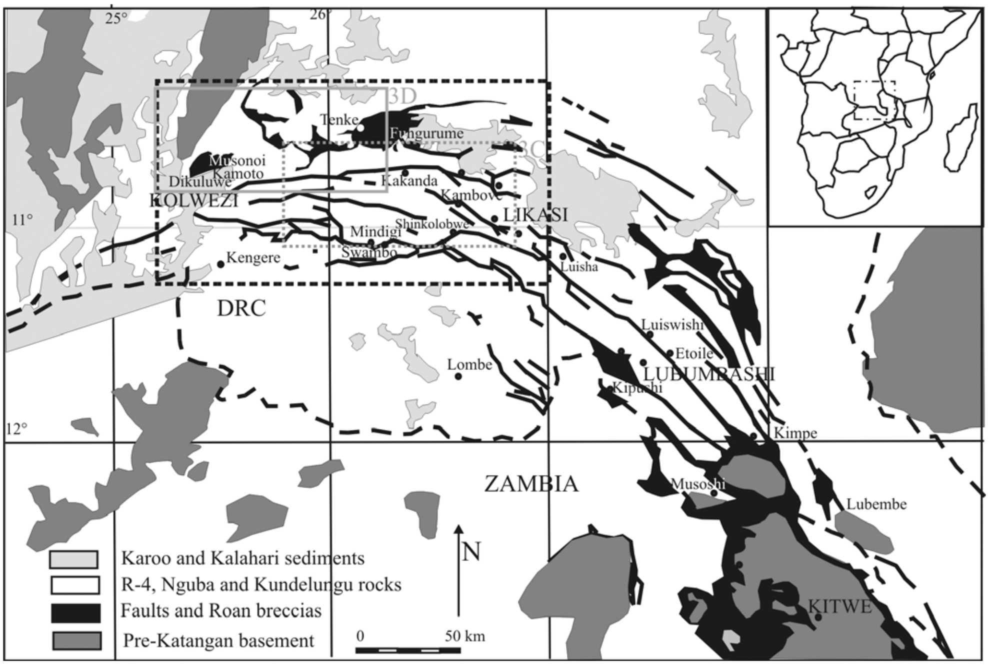

Fig. 1. Location of mineral occurrences in the Copperbelt (modified after François, 1974). Area of interest is indicated by a dark dashed rectangle, grey dashed rectangle is satellite image of Fig. 3C, grey full rectangle is Fig. 3D.

Although numerous metallogenic studies have been carried out to deduce the origin of these deposits, their formation still remains a matter of intense debate. The models proposed include synsedimentary, early diagenetic, late burial diagenetic or synorogenic origins. The synsedimentary or syngenetic theory links the precipitation of sulphides to the deposition of the host-sediments. According to Fleischer et al. (1976) and Garlick (1989), the copper came from streams and reacted with hydrogen sulphide in anoxic standing water to form the mineralization. The model was based on the presence of sulphidic bedding planes eroded by scour channels, slump folded ore horizons (Fleischer et al., 1976; Garlick, 1962, 1989) and a zonal sequence of bornite–chalcopyrite–pyrite that follows the direction of the sub-marine currents (Garlick, 1962). However, this model has been invalidated based on the lack of systematic correlation between transgressive/regressive events and sulphide zonation and on the discontinuity of the mineralization within a single lithostratigraphic unit in Zambia (Annels, 1974; Sweeney and Binda, 1994). Nevertheless, a synsedimentary to very early diagenetic origin is still favoured by Okitaudji (1989, 1992, 2001) for the Cu–Co deposits of Katanga in the DRC.

Bartholomé et al. (1971, 1972) and Bartholomé (1974) proposed a diagenetic, pre-deformation timing for the Cu–Co mineralization at Kamoto at the western end of the Lufilian fold-and-thrust belt. In this model an early sulphide generation formed during deposition and early diagenesis of the host-rocks, followed by a second sulphide generation due to the interaction of the hostsediment and its pore water with a metal-bearing brine. The unknown origin of the fluid, and the metal as well as the exact timing of the mineralization, led to numerous variations on the diagenetic model (e.g. Annels, 1989; Cailteux, 1974; Dejonghe and Ngoyi, 1995; Lefebvre, 1989; Selley et al., 2005; Unrug, 1988).

McGowan et al. (2003) presented field and isotopic data for the Nchanga deposit in the Zambian sub-province that indicate a replacive origin for this deposit, possibly during deformation of the host sequence. Wendorff (2000a) suggested that part of the stratiform mineralization formed by the precipitation of metals in the foreland of advancing thrust sheets during the Lufilian orogeny.

The aim of this paper is to demonstrate that several, often successive mineralization processes played an important role in the formation of the economic Cu–Co ore deposits in the western part of the Copperbelt. It is based on a compilation of available data from unpublished archives, combined with an interpretation of satellite imagery, a reconstruction of the paragenesis of the Cu–Co ore deposit at Musonoi and Kamoto (Kolwezi, Katanga, DRC) and a microthermometric study of fluid inclusions in authigenic quartz associated with the main mineralizing phase.

2. Geological setting

The Cu–Co deposits occur in the Neoproterozoic Katanga Supergroup of the Lufilian belt that formed during the pan-African orogeny (ca 560–550 Ma; Cahen et al., 1984; Kampunzu and Cailteux, 1999; Porada and Berhorst, 2000). The Katangan sediments started to be deposited in an intra-cratonic rift (Porada and Berhorst, 2000; Unrug, 1988) or in an epicontinental marine embayment (Jackson

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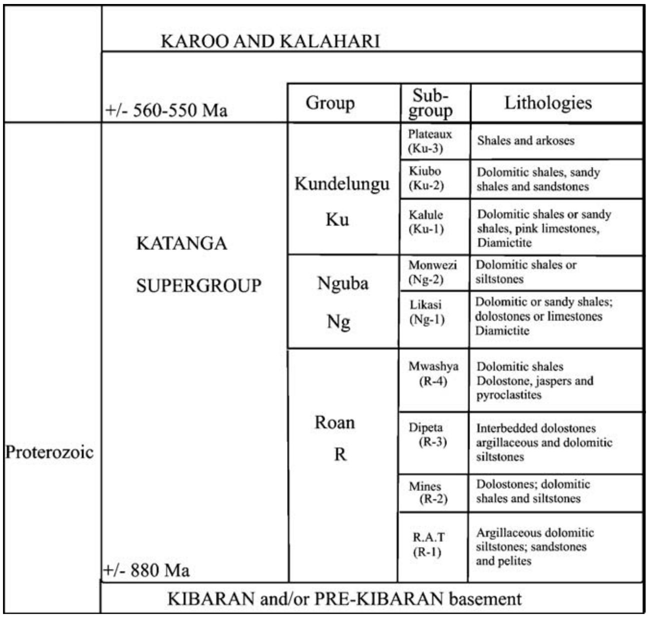
et al., 2003), which formed on a Palaeoproterozoic basement. The underlying pre-Katangan basement is poorly studied in Katanga and what is known in northern Zambia has been documented by Key et al. (2001) and Rainaud et al. (2002).

The Katanga Supergroup consists of a 5–10 km thick sequence that can be subdivided into three groups based on two regionally extensive diamictites. From the bottom to the top, the Katanga Supergroup is divided into the Roan, the Nguba and the Kundelungu Groups (Fig. 2; Cailteux et al., 2005). The Roan is subdivided into four subgroups, i.e. R-1 to R-4 Subgroup. R-1 consists of chlorite-rich dolomitic sandstones, known as the ‘‘Roches Argilo-Talqueuses (RAT)’’. The Mines Subgroup (R-2) is divided into three formations: the Kamoto Dolomite (R-2.1), the Dolomitic Shale (R-2.2) and the Kambove Dolomite (R-2.3; Cailteux and Kampunzu, 1995; François, 1987). Two Cu–Co deposits occur in the Mines Subgroup (François, 1987; Oosterbosch, 1951), one at the base of the Kamoto Dolomite and one at the base of the Dolomitic Shale. The Dipeta Subgroup, forming R-3, is characterized by alternating dolomites and argillaceous dolomitic sandstones. The uppermost part of the Roan (R-4) consists of dolomitic or carbonaceous shales and silicified dolomites of the Mwashya Subgroup.

The Nguba-Group contains, at its base, a diamictite (‘‘Grand Conglomérat’’) followed by dolomitic or sandy shales and carbonates, all forming part of the Likasi Subgroup. The overlying Monwezi Subgroup consists of dolomitic shales and siltstones.

The base of the uppermost Kundelungu Group is again characterized by a diamictite (‘‘Petit Conglomérat’’), which together with the overlying dolomitic or sandy shales and pink limestones, forms the Kalule Subgroup. The Kundelungu Group is further subdivided into the Kiubo and Plateaux Subgroups. The Kiubo Subgroup is characterized by dolomitic or sandy shales and sandstones and the Plateaux Subgroup by shales and arkoses (Cailteux et al., 1994; Dumont et al., 1997). In the western part of the Copperbelt, the rocks belonging to the Katanga Supergroup have been subjected to a lower greenschist metamorphism, which resulted in the formation of sericite and chlorite (François, 1974; Unrug, 1988).



		Group	Sub-group	Lithologies
	KAROO AND KALAHARI			
	+/- 560-550 Ma			
Proterozoic	KATANGA SUPERGROUP	Kundelungu Ku	Plateaux (Ku-3)	Shales and arkoses
			Kiubo (Ku-2)	Dolomitic shales, sandy shales and sandstones
			Kalule (Ku-1)	Dolomitic shales or sandy shales, pink limestones, Diamictite
		Nguba Ng	Monwezi (Ng-2)	Dolomitic shales or siltstones
			Likasi (Ng-1)	Dolomitic or sandy shales; dolostones or limestones Diamictite
		Roan R	Mwashya (R-4)	Dolomitic shales Dolostone, jaspers and pyroclastites
			Dipeta (R-3)	Interbedded dolostones argillaceous and dolomitic siltstones
			Mines (R-2)	Dolostones; dolomitic shales and siltstones
			R.A.T (R-1)	Argillaceous dolomitic siltstones; sandstones and pelites
	+/- 880 Ma			
	KIBARAN and/or PRE-KIBARAN basement			

Fig. 2. Stratigraphy of the Katanga Supergroup in Democratic Republic of Congo (modified after Cailteux et al., 2005).

Wendorff (2000b, 2005) proposed an alternative interpretation of the stratigraphy, with the absence of the Lower Roan in the Democratic Republic of Congo. This subject forms a matter of intense discussion (e.g. Cailteux et al., 2005; Kampunzu et al., 2005) and does not form the scope of this article.

The entire Lufilian belt can be divided into sub-regions, of which the Katangan Copperbelt in the DRC belongs to an outer unit of the arc. This unit is considered to be composed of a stack of thin-skinned thrust sheets transported on a detachment plane that cuts the basal part of the Roan. Upright or outward verging tight folds with axes traceable for distances of 50–175 km are typical within the thrust sheets. The thrust sheets occur together with large megabreccia that may have a tectonic origin (Lefebvre, 1980; François, 1974; Cailteux, 1990; Cailteux and Kampunzu, 1995), although some authors favour a salt tectonic (Jackson et al., 2003) or a sedimentary origin for at least some of the breccia (Wendorff, 2000a, 2005).

The main deformation phase in the Lufilian belt, is dated at 560–550 Ma (Porada and Berhorst, 2000; Rainaud et al., 2002). During the Lufilian orogeny, the Katangan basin closed, leading in the western part of the Copperbelt to the development of predominantly north-verging folds, thrusts and thrust sheets (Demesmaecker et al., 1962; Kampunzu and Cailteux, 1999). Deformation started in the south and progressed northward, where the emplacement of some of the thrust sheets might have been coeval with deposition of Late Kundelungu sediments (Kampunzu and Cailteux, 1999).

3. Cu–Co mineralization in the western part of the Katanga fold-and-thrust belt

A systematic overview has been made of all documented mineral occurrences in the western part of the Copperbelt in Katanga (DRC). The study area, extending from Kolwezi to Likasi in the Katanga Copperbelt, was selected based on data and maps available from the archives of the Royal Museum for Central Africa (RMCA, Tervuren, Belgium) (Demesmaecker et al., 1962; François, 1973, 1980; Lagmouche et al., 2004; Oosterbosch, 1962). Data on 155 mineral occurrences were collected from the archives and were compiled with detailed information on each of the localities described. From each mineral occurrence or ore deposit, the co-ordinates of the mineralization, the host-rock, the type of deposit (i.e. stratiform, vein type,

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supergene enrichment), type of metals (i.e. copper, copper–cobalt, other: e.g. U, Zn, Pb, Ge, Au), metal grades, estimated reserves, structural setting and proposed genesis are summarized.

The classification of the deposit as stratiform, supergene enrichment and vein types is adopted from François (1973). However, it must be noted that stratiform mineralization could have been submitted to supergene enrichment, whereas supergene mineralization could mimic a stratiform occurrence. In this study, supergene mineral occurrences are considered as the result solely of late enrichment and mobilization and, therefore, have different characteristics as the stratiform and vein-type mineralization. They consist predominantly of Cu-oxides (e.g. cuprite), Cu-carbonates (e.g. malachite) and Cu-silicates (e.g. chrysocolla), whereas the stratiform and vein-type are primarily a sulphide mineralization. Mineral occurrences without any information about their occurrence and characteristics in the archives of the RMCA, i.e. only the location is known, are classified as "unknown". A mineralization is classified as economically significant if a mine or a potential exploitation is mentioned in literature (François, 1973).

Table 1 shows an overview of the results obtained from the archives. The mineral occurrences are grouped according to the type of metals present, the deposit type, the host-rock and the economic significance of the deposit. Stratiform mineralization forms the largest group (97 of 155). Of this group, the majority – all except four – of the deposits occur in the R-2. About 25% of the stratiform mineralization are Cu only deposits (27 of 97) and almost half contain Cu in association with Co (48 of 97). Stratiform mineralization is hosted predominantly in rocks belonging to R-2 (93 of 97 deposits). Only 4 of 97 stratiform occurrences can be found in rocks belonging to the R-3, R-4, Nguba or Kundelungu strata. The second largest group results from supergene enrichment (36 occurrences). The "supergene enrichment" deposits are present in sediments that range in stratigraphic position from R-2 to Kundelungu. They consist dominantly of Cu without Co. This can be explained by the relatively limited mobility of Co in near-surface conditions (Rose, 1989). Deposits that formed by supergene enrichment are mainly present in Roan rocks (24 of 36 deposits). Only 5 of 36 occurrences of the supergene enrichment type are located in R-2. The third group with seven occurrences consists of vein-type mineralization and includes deposits such as Shinkolobwe and Swambo. Finally, 15 mineral occurrences could not be classified and are termed unknown.

Based on this systematic overview of mineral occurrences in the western part of the Lufilian fold-and-thrust belt in Katanga, it can be concluded that the majority of Cu and Cu–Co mineralization is stratiform and occurs in R-2 rocks, while mineralization in rocks younger than R-2, is mainly due to the remobilization of existing primary mineralization by supergene processes.

Table 1
Overview of the different mineral occurrences in the western part of the Copperbelt in the Democratic Republic Congo

Ore type	Metals	Economic mineralization							Non-economic mineralization							Total mineralization/stratigraphy							Total type/metal			Total/type
		R	R2	R3	R4	Ng	Ku	?	R	R2	R3	R4	Ng	Ku	?	R	R2	R3	R4	Ng	Ku	?	Cu	CuCo	other	
Stratiform	Cu		9							16				2			25				2		27			97
	CuCo		30							16			1	1			46			1	1			48		
	Other		15							7							22								22	
Supergene enrichment	Cu		2	3	1	2	1		1		6	4	9			1	2	9	5	11	1	0	29			36
	CuCo		1		2						1	1					1	1	3					5		
	Other		2												2										2	
Vein	Cu																					2	2			7
	CuCo																									
	Other		2			1		1						1			2			1	1	1			5	
Unknown	Cu			1					4					5		4		1			5		10			15
	CuCo		1							2	1						3	1						4		
	Other														1							1			1	
Total/stratigraphy		0	62	4	3	3	1	1	5	41	8	5	10	9	3	5	103	12	8	13	10	4	70	57	28	155

The mineral occurrences are grouped according to deposit type, hostrock and the economic significance of the deposit. R = deposit in Roan Group, R-x = Roan Subgroup, Ng = Nguba, Ku = Kundelungu, ? = unknown age of hostrock. Mineral occurrences with a different metal content as Cu and Co-like U, Ni, Pb, Cd, Ge, Ba, Au, Fe, Mn, Mo, Re, V, Pd- are grouped under "other" (François, 1973).

4. Satellite imagery and aerial photography

Satellite images and aerial photographs have been interpreted to identify geological structures and lineaments. Lineaments have been defined as "a linear topographic feature of regional extent that is believed to reflect crustal structure" (Hobbs et al., 1976). Structural and morphological elements are combined into lineaments of composite nature. During this study, LANDSAT images have been used with a spatial resolution of $28.5 \times 28.5\ m^2$/pixel. The data have been integrated in a Geographic Information System (GIS, MapInfo Professional Version 5.5). Layers with the location and characteristics of the mineral deposits, the geological map and the interpreted structural features have been combined to identify relationships between mineralization, stratigraphy and geological structures.

On the satellite images, ridges formed by rocks resistant to erosion are easily identified (Fig. 3A and B). By combining the layer of the satellite images with the layer of the

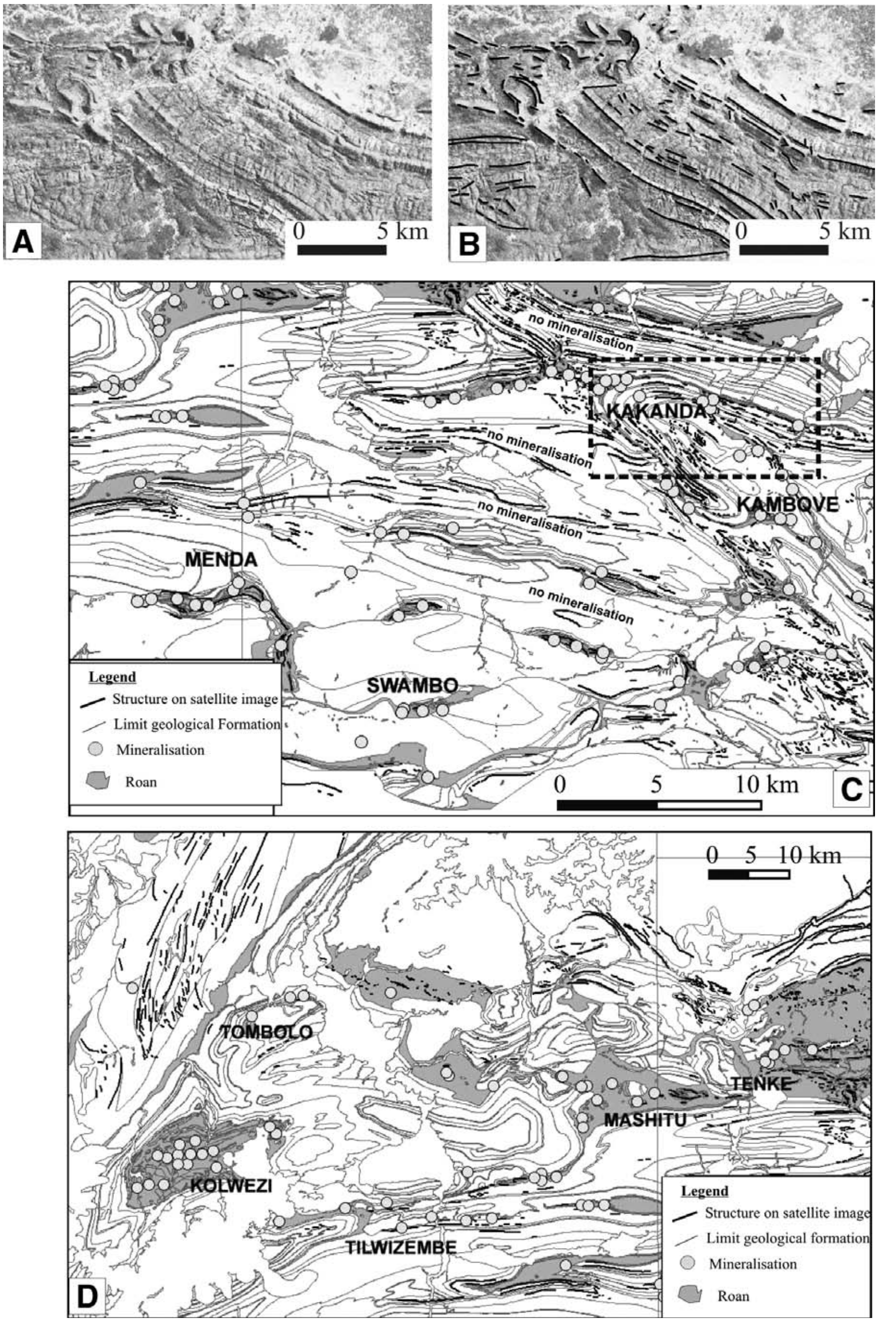

Fig. 3. (A) Unprocessed satellite image. (B) Processed satellite image with indication of ridges that correspond to relatively more resistant layers to erosion. (C) Map showing the relationship between the geology, mineralization and structures interpreted from satellite images. Area is also indicated by grey dashed rectangle in Fig. 1. Black rectangle shows outline area of the satellite image of Figs. 3A and B. (D) The intensely mineralized areas of Kolwezi and Mashitu show minor to no structures on satellite images.

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geological map, it is possible to relate these ridges with a certain stratigraphical interval and/or with structural features. For example in Fig. 3C, ridges consisting mainly of R-2 sediments can be identified along the margins of thrust sheets and along faults in these thrust sheets. The ridges in the central part of the thrust sheets consist dominantly of Nguba (Ng) or Kundelungu (Ku) Group rocks. In addition, by combining the satellite images with layers containing the description and location of the mineral occurrences, a clear relationship can be observed between the ridges and Cu–Co mineralization. With the exception of the Kolwezi and Mashitu regions, the stratiform mineralization can be related with ridges marking the margins of thrust sheets and faults along strike (Fig. 3D), since these consist mainly of rocks belonging to the R-2 Subgroup. This observation confirms a well-known exploration tool applied to the Katangan Copperbelt. Although the Kolwezi klippe and the Mashitu area are intensely mineralized, no geological structures can be identified. This could be due to the intense mining activity, with the omnipresence of mining dumps and/or the presence of strongly deformed Roan sediments. Only minor stratiform mineralization is observed associated with the ridges in the central part of the thrust sheets. However, this lack is not surprising since Roan rocks are missing. Four stratiform mineral occurrences are identified inside the thrust sheets (Kabulo North, Kafumvua South, Musoko North and Luwowishi; François, 1973, 1974), which occur in Kundelungu rocks. They are described as stratiform deposits (François, 1974) and are associated with lineaments. Malachite has been described from these locations.

Mineralization formed by supergene enrichment can be found along ridges in the central part of thrust sheets, along their margins and along faults in the thrust sheets.

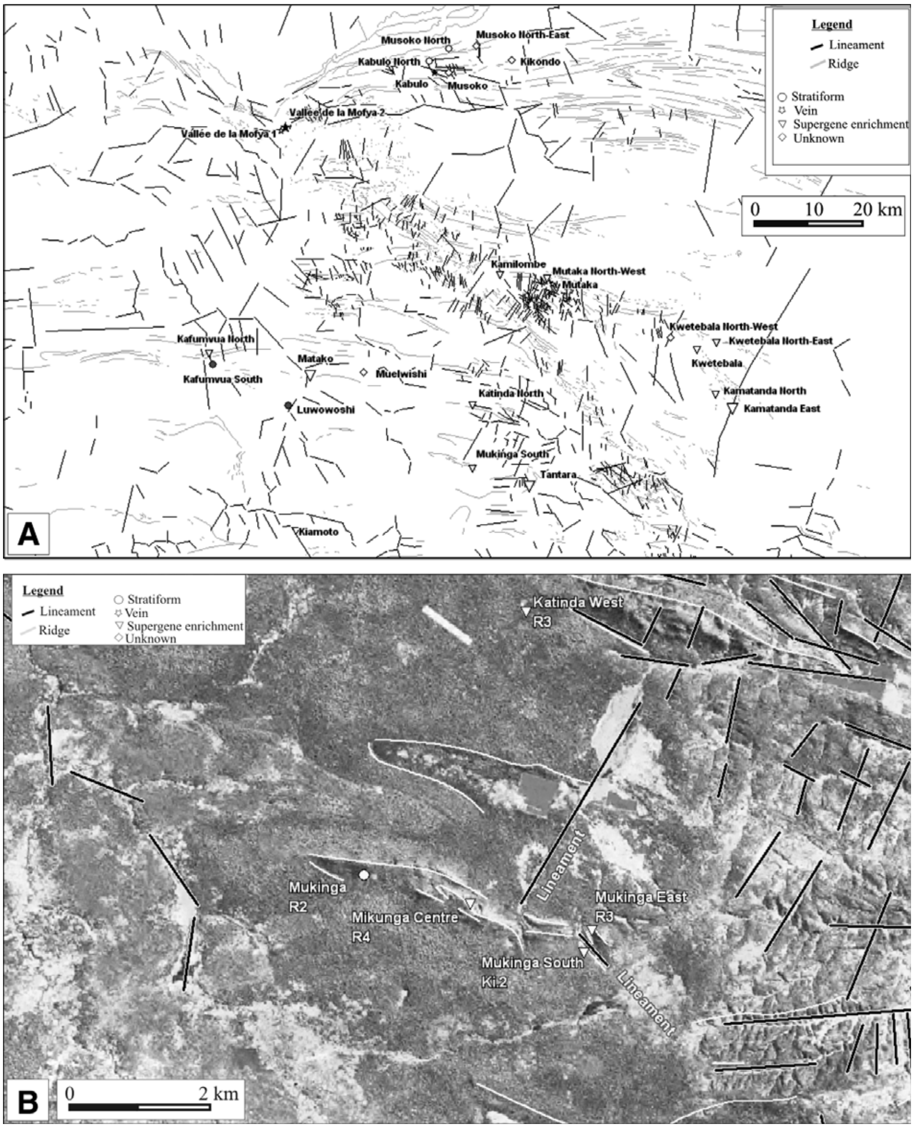

Fig. 4. (A) Mineralization outside the R-2 often shows a relationship with lineaments. (B) Mukinga-South, East and Centre are ore deposits of the enrichment type in respectively the Ng-2, R-3 and R-4 and occur along lineaments. The Mukinga stratiform deposit occurs in the R-2 and shows no direct relation with a lineament.

Table 2
Table showing relation between the economic significance of mineral occurrences (François, 1973) in the western part of the Copperbelt in the DRC and the presence of a nearby lineament

Deposit type	Stratigraphy	Economic significancy	Lineament
Stratiform	R-2	37 economic	30
		38 non-economic	17
	R-3	/	/
		/	/
	R-4	/	/
		/	/
	Ng	0 economic	0
		1 non-economic	0
	Ku	0 economic	0
		3 non-economic	0
Supergene enrichment	R-2	3 economic	3
		0 non-economic	0
	R-3	2 economic	2
		4 non-economic	4
	R-4	3 economic	3
		5 non-economic	2
	Ng	2 economic	2
		9 non-economic	6
	Ku	1 economic	1
		0 non-economic	0
Vein	R-2	2 economic	2
		0 non-economic	0
	R-3	/	/
		/	/
	R-4	/	/
		/	/
	Ng	1 economic	1
		0 non-economic	0
	Ku	0 economic	0
		1 non-economic	1

Occurrences in the areas of Kolwezi and Mashitu are not taken in account. The slash indicates that no mineralization has been described at this stratigraphic level. R-x = Roan Subgroup, Ng = Nguba, Ku = Kundelungu.

The majority of supergene mineralization within the R-2-3-4, Nguba and Kundelungu is located along lineaments (e.g. Fig. 4A). For example, in the Mukinga area, the stratiform R-2 mineralization is located along ridges of Roan rocks, whereas the Mukinga-South deposit, present in the Nguba-Group and described as a mineralization that formed by supergene enrichment, occurs along a small lineament with a NW–SE orientation (Fig. 4B). The structures expressed as lineaments could have formed pathways for the remobilizing fluids that leached earlier stratiform mineralization and formed the mineral occurrences in the Roan 3–4, Nguba and Kundelungu strata. Also, 6 of the 7 vein-type deposits are related to lineaments. However, for the Swambo mineralization in R-2 rocks, no lineament has been identified.

In addition, the majority of the described economic mineralization formed by supergene enrichment is related to lineaments (11 of 11 deposits, Table 2). This observation is even valid for the major stratiform Cu and Cu–Co deposits belonging to the R-2 group. Thirty of 37 economic stratiform deposits can be related with a lineament, whereas only 17 of 38 non-economic deposits are associated with a lineament (Table 2). Economic stratiform Cu–Co mineralization seems to be situated at the intersection of R-2 strata and a crosscutting lineament (Fig. 5).

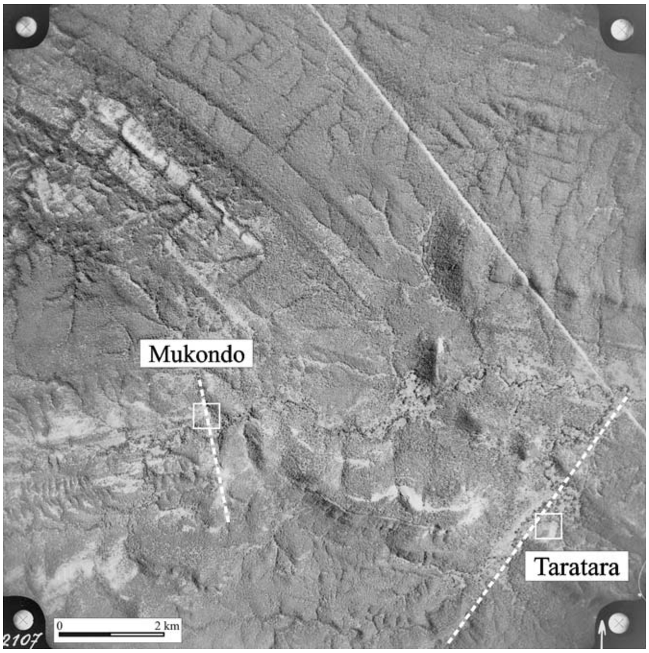

Fig. 5. Aerial photograph showing the location of economic stratiform mineralization of Mukondo and Taratara at the intersection of ridges formed by R-2 rocks and a lineament (dashed line).

5. Petrography

Detailed petrographic and microthermometric investigations have been carried out on Cu–Co mineralization in the western part of the Copperbelt. Mineral occurrences with another metal content (e.g. U, Zn, Pb, Ge, and Au; e.g. Cailteux, 1997; Loris, 1996; Meneghel, 1981) have not been studied here.

Samples have been taken from the Cu–Co mineralization at the Kamoto-Principal and Musonoi mines to construct a paragenetic sequence. These deposits are located in the Kolwezi klippe (westernmost part of the Katanga Copperbelt). Musonoi is located at a few kilometres west from Kamoto (Bartholomé et al., 1972; Bartholomé, 1974). Both mineralization have a km-scale extension. A continuous sampling of the R-1.4 to R-2.3 rocks was possible thanks to the collections of the University of Liege (Belgium) and the K.U. Leuven (Belgium).

In this study, only rocks belonging to R-2.1 and the lower part of R-2.2 have been studied in detail (Fig. 6). The deposits at Kamoto and Musonoi consist of a lower (LO) and an upper orebody (UO), separated by a low-grade stromatolitic dolomite (RSC: "Roches Siliceuses Cellulaires"). The lithology of the "lower" orebody hostrock consists of an alteration of chloritic–dolomitic siltite and stratified and silicified dolomites, whereas the hostrock of the "upper" orebody consists mainly of dolomitic shales,

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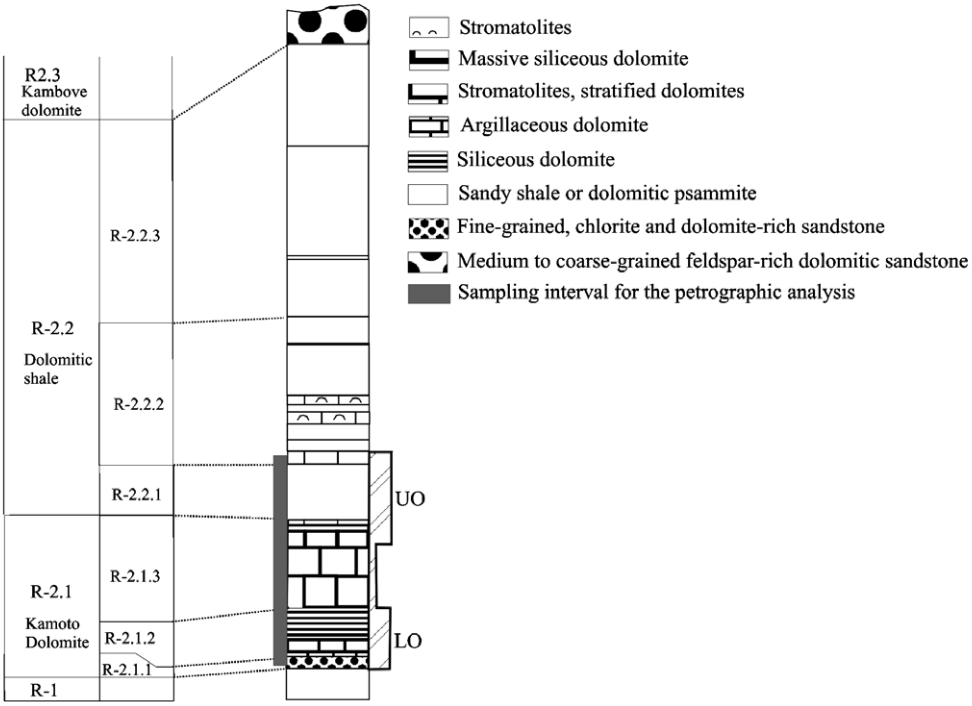

Fig. 6. Stratigraphic section with indication of the lower orebody (LO) and upper orebody (UO). The stratigraphic sequence is for Musonoi (after François, 1973), but the stratigraphy at Kamoto is almost identical. R = Roan Group, R-x = subgroup, R-x.x = Formation, R-x.x.x = level.

dolomites and fine-grained sandstones. Bedding shows millimetre to centimetre layering, which reflects grain-size and mineralogical variations (François, 1973).

Polished thin sections have been studied by transmitted and incident light microscopy and cold cathodoluminescence petrography. A Technosyn Cold Cathodo Luminescence Model 8200 MK II was operated at 10–16 kV, 5.5 Pa, 5 mm beam width and a current below 1000 μA. Ore minerals have been identified by incident light microscopy using the criteria from Uytenbogaardt and Burke (1986) (Fig. 7).

The Roan sediments are composed of carbonate, quartz, detrital muscovite and some minor amounts of detrital chlorite and tourmaline. Shortly after sedimentation, framboidal and euhedral pyrite formed (Fig. 8A and B). Nodules, consisting of anhydrite and gypsum formed in the evaporitic environment and an early diagenetic dolomitisation, with non-luminescent dolomite, occurred. This early diagenetic dolomite also partly replaced the evaporate nodules or precipitated in dissolution cavities. The pyrite is overgrown and partly replaced by chalcopyrite (Fig. 8A). It should be noticed that the pyrite and chalco-

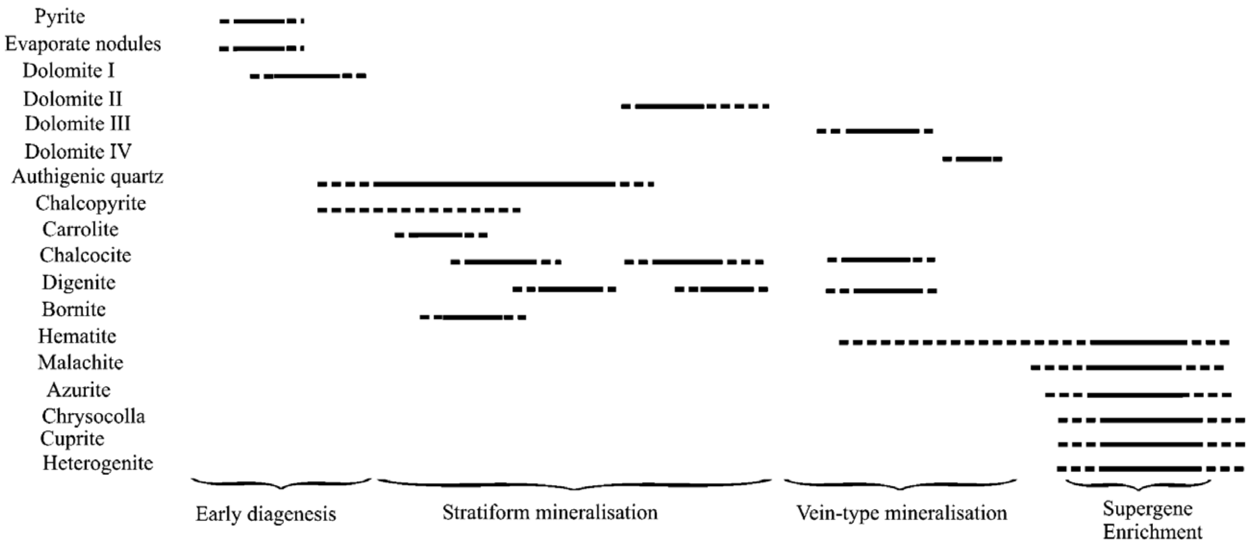

Fig. 7. Reconstruction of the paragenesis at Kamoto and Musonoi. Different stages are explained in the text.

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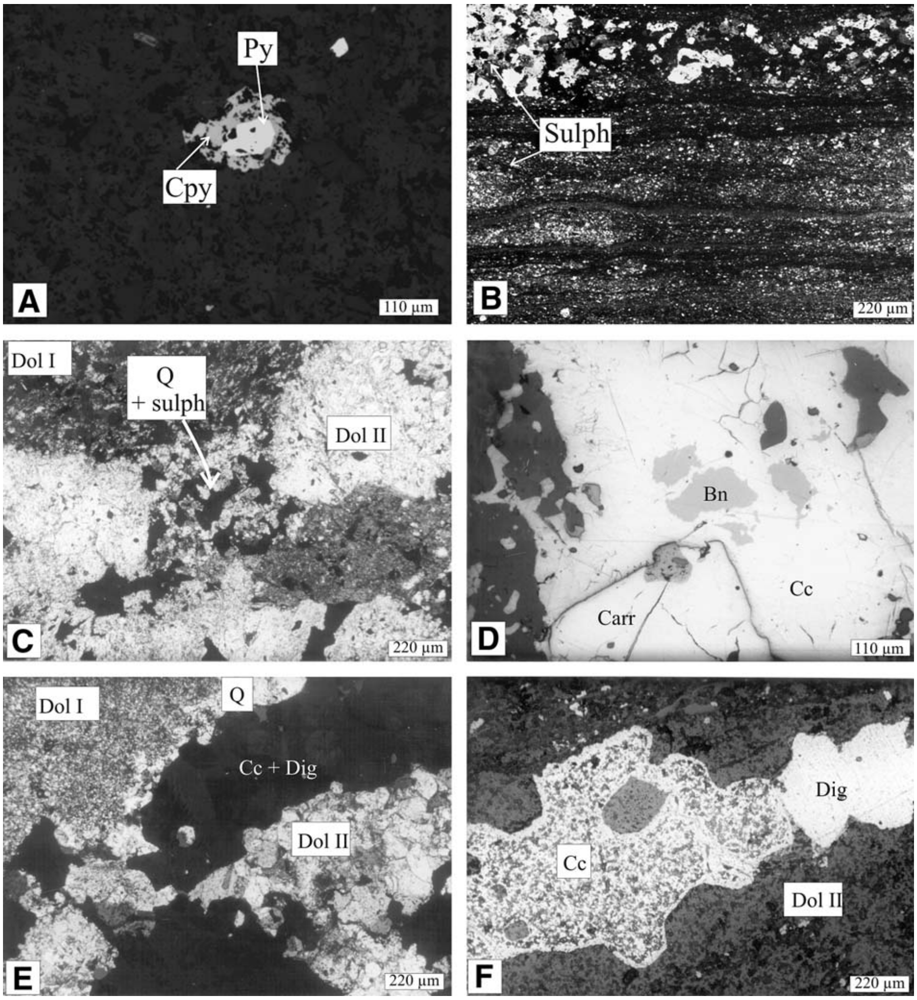

Fig. 8. (A) Early diagenetic pyrite (Py), overgrown by chalcopyrite (Cpy). Plane polarized light. (B) Pyrite and chalcopyrite have only been identified in the layers above the upper Orebody. Crossed nicols. (C) Authigenic quartz with sulphides, followed by the second dolomite generation (Dol II). Crossed nicols. (D) Sulphides associated with quartz are carrolite (Car), bornite (Bn) and chalcocite (Cc). Plane polarized light. (E) Second generation of dolomite (Dol II), associated with chalcocite (Cc) and digenite (Dig) that formed after quartz (Q). Crossed nicols. (F) Detailed microphotograph showing chalcocite (Cc) and digenite (Dig) associated with the second dolomite generation (Dol II). Plane polarized light.

pyrite have only be observed starting from the upper part of the "upper" orebody (R-2.2.1.2), where other ore minerals are lacking.

After this early diagenetic dolomitisation, authigenic quartz (Fig. 8C) precipitated in rocks of the lower and upper orebody and the low-grade intermediate zone. This authigenic quartz is intimately associated with the main phase of sulphide precipitation, consisting of carrolite, bornite, digenite and chalcocite (Fig. 8D). No traces of pyrite or chalcopyrite have been observed in the "lower" and "upper orebody". The main mineralization phase is followed by a second dolomite generation (Fig. 8E). The first dolomite generation has sometimes been recrystallized and shows the same luminescence as the second dolomite generation. Digenite and corroded chalcocite grains occur with this second dolomite cement (Fig. 8F). This dolomite has a bright orange luminescence, which shows growth zoning (Fig. 9A). A third, coarse-crystalline dolomite cement (Fig. 9B) occurs together with chalcocite, digenite and hematite in fractures and concentrated in spots or irregular layers (Fig. 9C). Hematite crystallized as an alteration product of the sulphides. This third, dull orange luminescent dolomite is overgrown by a bright ochre-yellow luminescent intensely zoned, fourth dolomite generation (Fig. 9D). The fractures/veins that are filled with the two last dolomite generations and the chalcocite–digenite–hematite mineralization crosscut the compacted rock with the stratiform carrolite–bornite–chalcocite–digenite mineralization. The primary stratiform and vein-type sulphide mineralization is overprinted with Cu-oxides, Co and Cu-hydroxides and Cu-silicates, which formed by supergene enrichment processes.

Based on the petrographic study of the mineralization at Kamoto and Musonoi, it becomes clear that the Cu–Co mineralization is the result of several succeeding processes.

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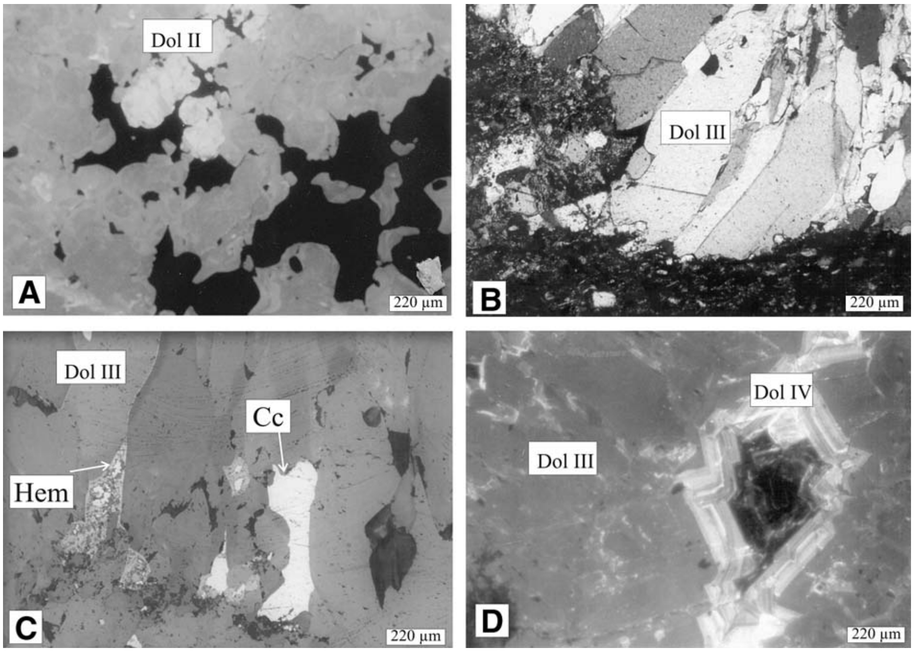

Fig. 9. (A) Cathodoluminescence photograph of the second dolomite generation (Dol II), showing growth zoning. Cathodoluminescence photograph. (B) Third dolomite generation (Dol III). Crossed nicols. (C) Hematite and chalcocite mineralization associated with the third dolomite generation (Dol III). Plane polarized light. (D) Third (Dol III) and fourth dolomite generation (Dol IV), occurring in a vein. Cathodoluminescence photograph.

6. Microthermometry

Samples were selected to study fluid inclusions in the authigenic quartz, which is interpreted to be contemporaneous with the main stage of the "stratiform" mineralization (see also Oosterbosch, 1962; Bartholomé et al., 1972; François, 1974). In this preliminary study, a doubly polished section was prepared from the lower orebody (R-2.1.2; RSF: "Roches Siliceuses Feuilletées") of the Musonoi deposit, and also from both the upper orebody (R-2.2.1; BOMZ: "Black Ore Mineral Zone") and the low-grade intermediate zone (R-2.1.3; RSC: "Roches Siliceuses Cellulaires") of the Kamoto deposit. Only quartz has been studied microthermometrically. Earlier microthermometric results obtained by Pirmolin (1970) and Ngongo (1975) on dolomite from Kamoto, Shinkolobwe, Kambove-Ouest and Luiswishi orebodies have been interpreted by Okitaudji (1989) to be related to stretched inclusions and, therefore, the homogenization temperatures cannot be used to deduce ambient precipitation temperatures. Indeed, inclusions in carbonates are easily stretched during subsequent burial or tectonic deformation (Goldstein, 1986; Barker and Goldstein, 1990).

A detailed description of the sample preparation technique and of the measurement procedure has been given by Muchez et al. (1994). Measurements were carried out on a Linkam THMSG 600 stage mounted on an Olympus BX60 microscope with a 100x magnification lens in order to observe small inclusions ($\leqslant 3$ µm). The heating and freezing cycles on this Linkam stage are completely software controlled. Reproducibility was within 0.2 °C for the melting temperatures and $\leqslant 5$ °C for the total homogenization temperature. The stage was calibrated between −56.6 and 374.1 °C by using synthetic inclusions.

The fluid inclusions measured typically occur as individual inclusions, clustered or concentrated in zones within the authigenic quartz crystals (Fig. 10A and B). Some of them occur in growth zones and a primary origin can be proposed. In addition, the inclusions present in the authigenic quartz do not occur in later carbonate generations. At room temperature, all fluid inclusions are two-phase (L + V), while inclusions in younger dolomite generations have multiple daughter crystals (see also Pirmolin, 1970; Ngongo, 1975). Therefore, all inclusions in the quartz are interpreted to predate the precipitation of subsequent carbonate cement generations (cf. Wilkinson, 2001).

Two-phase inclusions have been identified in the authigenic quartz associated with mineralization in the RSC, the RSF and the BOMZ. Due to the small size of the inclusions ($\leqslant 5$ µm), the eutectic melting was only visible in a limited number of inclusions in each sample and is approximately −21 °C, which is characteristic for the H_2O–NaCl system. Also due to the small size of the inclusions, only a limited number of final melting and homogenization temperatures could be measured.

The ice melting temperatures (Tm_{ice}) of fluid inclusions in the BOMZ vary between −11.8 and −8.4 °C (average value of −11 °C; Fig. 8C), whereas Tm_{ice} values in RSF and RSC vary respectively between −14.8 and −5.4 °C (average value of −9 °C; Fig. 10C) and between −11.3 and −6.2 °C (average value of −9 °C; Fig. 10C). The inclusions in BOMZ homogenize between 127 and 192 °C (average value of 162 °C; Fig. 10D), while Th_{Tot} for the RSF and RSC fall respectively between 105 ° and 188 °C (aver-

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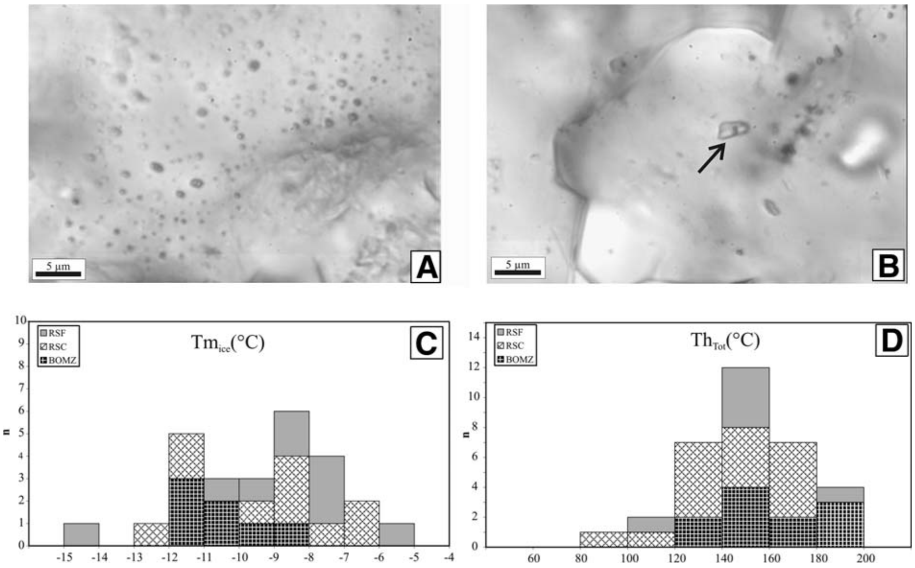

Fig. 10. (A) Numerous tiny aqueous inclusions clustered in zones in authigenic quartz associated with the main sulphide mineralization. (B) Detail of a two-phase aqueous fluid inclusion in authigenic quartz (C). Ice melting temperatures (Tm_{ice}) of fluid inclusions in authigenic quartz (D). Homogenization temperatures (Th_{Tot}) of fluid inclusions in authigenic quartz. Doubly polished sections were prepared from samples from the lower orebody (R-2.1.2; RSF: "Roches Siliceuses Feuilletées") of the Musonoi mineralization and the upper orebody (R-2.2.1; BOMZ: "Black Ore Mineral Zone") and the low-grade intermediate zone (R-2.1.3; RSC: "Roches Siliceuses Cellulaires") of the stratiform Kamoto mineralization.

age value of 149 °C; Fig. 10D) and between 80 and 168 °C (average value of 140 °C; Fig. 10D).

The salinity and density have been calculated with the programme FLINCOR of Brown (1989), using the equation of state (EOS) of Brown and Lamb (1989). For BOMZ, the salinity calculated varies between 12.2 and 15.2 eq. wt% NaCl and the density is between 0.94 and 1.05 g/cm^3. The salinity and density calculated for the RSF vary respectively between 8.4 and 18.4 eq. wt% NaCl and between 0.95 and 1.08 g/cm^3, whereas for the RSC the values are between 9.4 and 15.3 eq. wt% NaCl and between 0.97 and 1.04 g/cm^3.

The microthermometric data indicates that the fluids found in the authigenic quartz in the lower orebody (RSF), the upper orebody (BOMZ) and the low-grade barren zone (RSC) have similar H_2O–NaCl compositions and spreads in homogenization temperature and salinity. Therefore, a single fluid is proposed for the formation of the main stage of the Cu–Co mineralization.

7. Discussion

7.1. Cu–Co mineralization and satellite imagery

A systematic study of the occurrence of the Cu–Co mineralization in the western part of the Katanga Copperbelt, combined with satellite imagery, confirms that the mineral occurrences are mainly stratiform (97 out of 155 deposits) and limited to the R-2 group (103 of 155). The stratigraphic control on the mineralization has already been widely described in literature (e.g. Demesmaecker et al., 1962; François, 1973; Oosterbosch, 1962; Unrug, 1988; Cailteux et al., 1994), i.e. mineralization occurs mainly in the Kamoto Dolomite and the Dolomitic Shales. These formations can often be identified by satellite imagery as they occur as ridges due to their resistance to weathering. These ridges, consisting of R-2 rocks, mark the margins of thrust sheets and faults along strike in these thrust sheets. The interpretation of satellite images and data on the mineralization indicates that mineralization outside the R-2 formed dominantly by supergene enrichment.

The majority of the described economic ore deposits are related to the presence of a lineament (Table 2). This is not only the case for the supergene mineralization, but also for the economic stratiform ore deposits belonging to the R-2 Subgroup. Economic stratiform Cu–Co mineralization seems to be situated at the intersection of the Roan strata and a crosscutting lineament. The latter could reflect a fracture zone or even faults that formed the migration pathway for descending waters that caused supergene enrichment. These fractures and faults could even provided the pathways for the upward migration of the mineralizing fluids (cfr. Brock, 1961; Selley et al., 2005 for the Zambian part of the Copperbelt). Also, Raybould (1978) proposed that the stratiform copper mineralization of the southern part of the Copperbelt are located along a northwest–southeast-trending lineament along which fluids migrated upwards from the basement to form the copper mineralization. However, a pre-orogenic origin of the lineaments cannot be demonstrated based on the present knowledge. Field work should be carried to investigate this relationship.

7.2. Synsedimentary to early diagenetic origin

The first sulphides precipitated in the stratiform mineralization are framboidal and euhedral pyrite, which pre-

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date the main copper mineralization (e.g. Oosterbosch, 1951; Bartholomé, 1974; Bartholomé et al., 1971, 1972; Cailteux, 1994). Framboidal pyrite is characteristic for a synsedimentary to early diagenetic precipitation. This sulphide precipitated at temperatures between 20 and 60 °C and at near-neutral pH due to bacteriogenic processes (cf. Bartholomé, 1974; Fleischer et al., 1976; Sweeney et al., 1986, 1991; Okitaudji, 1992, 2001).

A purely syngenetic origin of the stratiform Cu–Co mineralization is abandoned based on the lack of systematic correlation between transgressive/regressive events and sulphide zonation and based on the discontinuity of the mineralization within a single lithostratigraphic unit (Annels, 1974; Sweeney and Binda, 1994; Cailteux et al., 2005).

7.3. Diagenetic origin

The association of the cobalt mineralization and a major part of the copper mineralization with diagenetic minerals (dolomite) indicates that both precipitated during further diagenesis (Bartholomé, 1974; Bartholomé et al., 1971, 1972; Cailteux et al., 2005; Dimanche, 1974; Unrug, 1988). This generation of sulphides consists of a first phase of carrolite, bornite, digenite and chalcocite, associated with authigenic quartz. No chalcopyrite is found in this "main ore stage". Chalcopyrite is only found above the Upper Orebody, where it replaces the early diagenetic pyrite. The absence of chalcopyrite in the main orebodies could be due to the large amount of available copper and the resulting formation of bornite rather than chalcopyrite. The main "ore stage" is followed by a second dolomite generation. Digenite and corroded chalcocite grains occur with this second dolomite cement. Since only one generation of non-luminescent dolomite preceded the precipitation of the authigenic quartz and the ore minerals, an early diagenetic origin is possible, however, cannot be fully demonstrated. The observation that also large pores are partly cemented by this non-luminescent dolomite generation favours a mineralization under shallow burial conditions. Also Sweeney et al. (1986) and Sweeney and Binda (1989, 1994) propose that the bulk of the sulphides formed before appreciable burial of the sediments.

Microthermometric results of fluid inclusions in the authigenic quartz indicate the presence of a fluid with a minimum temperature between 80 and 195 °C and a salinity between 8.4 and 18.4 eq. wt% NaCl. These data demonstrate that during the main mineralization relatively hot saline fluids migrated through the Roan. Pirmolin (1970) and Ngongo (1975) described two-phase inclusions in dolomite minerals from the Kamoto-Principal, Shinkolobwe, Kambove-Ouest and Luiswishi orebodies. No information is available on the petrography and paragenetic position of the fluid inclusions studied. The small inclusions yield temperatures around 70 °C and salinities of 7–10 eq. wt% NaCl. A similar temperature (110–170 °C) and salinity range (9–16 eq. wt% NaCl) as observed in the present study is reported by Annels (1989) for fluid inclusions in early quartz associated with pyrite, chalcopyrite, pyrrhotite and bornite from the Chambishi deposit (Zambian sub-province). Annels (1989) proposed a model that includes the upward migration of the mineralizing fluid along faults from the basement and a lateral fluid flow in permeable arenites and below impermeable horizons such as the Ore Shale.

7.4. Late diagenetic and orogenic mineralization

Mineralized sediments are commonly cut by multiple vein generations. The veins are filled with the dolomite generations III and IV and chalcocite–digenite–hematite. Numerous authors (e.g. Bartholomé et al., 1972; Bartholomé, 1974; Lefebvre, 1976; Cailteux et al., 1994; Dejonghe, 1997; Garlick, 1962; Hoy and Ohmoto, 1989; Maree, 1963; Winfield and Robinson, 1963) identified mineralizing phases associated with fractures and fissures.

Temperatures up to 400 °C are recorded from fluid inclusions in post-ore vein quartz from Musoshi (Richards et al., 1988) and Chambishi (Annels, 1989). These post-main mineralization high temperatures reflect the maximum burial and metamorphic temperatures reached in the area (Richards et al., 1988) or a possible magmatic event (Annels, 1989). Richards et al. (1988) obtained a U/Pb rutile age of 514 Ma for this late hydrothermal activity, which they related to compressional deformation and metamorphism associated with the Lufilian orogeny. This hydrothermal activity may have caused the remobilization and local concentration of copper-bearing minerals (see also Ngongo, 1975). A correlation between the origin of the Cu–Co stratiform ore deposits and the Lufilian orogeny was proposed for the Nchanga mineralization by McGowan et al. (2003).

Tectonic deformation and metamorphism during the Lufilian orogeny, although possibly resulting in a set of crosscutting (high-temperature) mineralized veins, seems – in general – not to have resulted in a major remobilization or redistribution of the sulphides (Hoy and Ohmoto, 1989; Sweeney et al., 1991; Sweeney and Binda, 1994; Winfield and Robinson, 1963). Minor remobilization of stratiform ores is shown by few crosscutting mineralized veins surrounded by centimetre wide zones within which stratiform sulphides have been depleted (Cailteux et al., 2005).

7.5. Supergene enrichment

The ore deposits became weathered during their exposure, which resulted in the formation of supergene enriched ore bodies. The latter dominantly formed in Roan rocks, but are also identified in Nguba and Kundelungu rocks. The intense meteoric alteration not only formed numerous secondary minerals, but the process also resulted in a major increase of the copper content (from a few percent up to 25% Cu), which is of great economic importance (e.g. Demesmaecker et al., 1962; Garlick, 1962; Horscroft, 1963; Lefebvre, 1974; Oosterbosch, 1962; Ralston, 1963).

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Our discussion indicates that, although the main phase of the mineralization in the Katanga Copperbelt in particular occurred during diagenesis in a general sense, sulphide mineralization more specifically appears to have occurred during different periods during diagenesis, finally followed by supergene enrichment in the near-surface environment. The relation between the occurrence of mineralization and the lineaments indicates that these lineaments played a significant role on the migration of at least the supergene fluids.

8. Conclusion

A multiphase origin of the Cu–Co ores in the western part of the Lufilian fold-and-thrust belt in the western part of Katanga (DRC) is proposed based on literature review and on new data from satellite imagery interpretation, archives compilation, petrography and fluid inclusion research. 155 mineral occurrences from the western part of the Katanga Copperbelt in the Democratic Republic of Congo (DRC) are reviewed. The majority of the Cu–Co occurrences is stratiform and occurs in R-2 sediments. On satellite images, these mineral occurrences can be located on ridges, marking the margins of thrust sheets and faults along strike. Mineral occurrences in strata outside the R-2 have mainly formed by enrichment due to remobilization in the supergene environment.

The combination of satellite imagery and data on the mineralization shows that economic mineralization – stratiform and enrichment – can be related to lineaments. Economic stratiform occurrences have been identified at the intersection of the R-2 and crosscutting lineaments. The latter reflect fracture zones or even faults that formed the migration pathways for descending waters that caused the supergene enrichment and upgrading of the "stratiform" primary mineralization.

The Cu–Co occurrences have often been attributed to a strictly synsedimentary, early diagenetic, burial diagenetic or synorogenic origin. Our work suggests that mineralization in the Copperbelt are the result of several superposed mineralizing events (from diagenesis up to supergene enrichment). However, the main phase of the stratiform Cu–Co mineralization in the Katanga Copperbelt occurred during diagenesis, well before the Lufilian orogeny. After the formation of framboidal pyrite during early diagenesis, Cu and Co-rich fluids (Th_{Tot} between 80 and 192 °C and salinity between 8.4 and 18.4 eq. wt% NaCl) circulated and formed the main mineralization.

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