Genesis of sediment-hosted stratiform copper–cobalt deposits, central African Copperbelt

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Abstract

The Neoproterozoic central African Copperbelt is one of the greatest sediment-hosted stratiform Cu–Co provinces in the world, totalling 140 Mt copper and 6 Mt cobalt and including several world-class deposits ($\geqslant$10 Mt copper). The origin of Cu–Co mineralisation in this province remains speculative, with the debate centred around syngenetic–diagenetic and hydrothermal-diagenetic hypotheses.

The regional distribution of metals indicates that most of the cobalt-rich copper deposits are hosted in dolomites and dolomitic shales forming allochthonous units exposed in Congo and known as Congolese facies of the Katangan sedimentary succession (average Co:Cu = 1:13). The highest Co:Cu ratio (up to 3:1) occurs in ore deposits located along the southern structural block of the Lufilian Arc. The predominantly siliciclastic Zambian facies, exposed in Zambia and in SE Congo, forms para-autochthonous sedimentary units hosting ore deposits characterized by lower a Co:Cu ratio (average 1:57). Transitional lithofacies in Zambia (e.g. Baluba, Mindola) and in Congo (e.g. Lubembe) indicate a gradual transition in the Katangan basin during the deposition of laterally correlative clastic and carbonate sedimentary rocks exposed in Zambia and in Congo, and are marked by Co:Cu ratios in the range 1:15.

The main Cu–Co orebodies occur at the base of the Mines/Musoshi Subgroup, which is characterized by evaporitic intertidal–supratidal sedimentary rocks. All additional lenticular orebodies known in the upper part of the Mines/Musoshi Subgroup are hosted in similar sedimentary rocks, suggesting highly favourable conditions for the ore genesis in particular sedimentary environments. Prelithification sedimentary structures affecting disseminated sulphides indicate that metals were deposited before compaction and consolidation of the host sediment.

The ore parageneses indicate several generations of sulphides marking syngenetic, early diagenetic and late diagenetic processes. Sulphur isotopic data on sulphides suggest the derivation of sulphur essentially from the bacterial reduction of seawater sulphates. The mineralizing brines were generated from sea water in sabkhas or hypersaline lagoons during the deposition of the host rocks. Changes of Eh–pH and salinity probably were critical for concentrating copper–cobalt and nickel mineralisation. Compressional tectonic and related metamorphic processes and supergene enrichment have played variable roles in the remobilisation and upgrading of the primary mineralisation.

There is no evidence to support models assuming that metals originated from: (1) Katangan igneous rocks and related hydrothermal processes or; (2) leaching of red beds underlying the orebodies. The metal sources are pre-Katangan continental rocks, especially the Palaeoproterozoic low-grade porphyry copper deposits known in the Bangweulu block and subsidiary Cu–Co–Ni deposits/occurrences in the Archaean rocks of the Zimbabwe craton. These two sources contain low grade ore deposits portraying the peculiar metal association (Cu, Co, Ni, U, Cr, Au, Ag, PGE) recorded in the Katangan sediment-hosted ore deposits. Metals were transported into the basin dissolved in water.

The stratiform deposits of Congo and Zambia display features indicating that syngenetic and early diagenetic processes controlled the formation of the Neoproterozoic Copperbelt of central Africa.

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1. Introduction

The Neoproterozoic Katangan Copperbelt of central Africa stretches on both sides of the border between Zambia and Democratic Republic of Congo (DRC; hereafter Congo). It hosts one of the world's greatest concentration of stratiform copper–cobalt deposits, representing more than half of the world's mineable cobalt and includes world-class Cu–Co deposits, e.g. Kolwezi, Tenke-Fungurume, Konkola-Chililabombwe, Nchanga, Nkana, Mufulira, each containing ⩾10 Mt copper. Total copper hosted in the Katangan basin of central Africa is close to 200 Mt if sub-economic (Cu ⩾ 1 wt.%) occurrences are included (data from Gécamines Mining Company for DRC and from Freeman, 1988 for Zambia). Copper and cobalt are associated with iron, and sometimes with anomalous concentrations of other metals (e.g. Ni, U, Ag, Au, PGM, Se, Mo, V, Te, As, Th). The ore is mainly made of disseminated sulphides forming stratiform orebodies hosted in fine-grained siliciclastic or dolomitic sedimentary rocks.

Since the discovery of the Copperbelt in the early 1900s, several metallogenic hypotheses were proposed to explain the primary source of metals and the mineralisation process. The historical review of these genetic theories is given in Sweeney et al. (1991a,b) and Sweeney and Binda (1994) for the Zambian Copperbelt. The epigenetic hypothesis suggests the introduction of hydrothermal mineralizing solutions after the deposition, lithification and deep burial of sediments. In this model, the hydrothermal fluids are supposed to originate from the emplacement of granite–granodiorite–tonalite bodies in the Copperbelt (Gray, 1929; Davidson, 1931; Jackson, 1932; Thoreau and du Trieu de Terdonck, 1932; Derriks and Vaes, 1956; Derriks and Oosterbosch, 1958; Darnley, 1960; Vaes, 1962). The existence of minor sulphide veins or veinlets within a few sediment-hosted copper deposits in Zambia (e.g. Nchanga) and in Congo (e.g. Shinkolobwe) and within a few Zambian granites was taken as a support for this interpretation. However, an unconformable erosional contact occurs between the granitoids and the overlying Katangan sedimentary succession in Zambia (Garlick, 1961a; Binda, 1972). This is supported by U–Pb zircon geochronological data (Armstrong et al., 1999; Rainaud et al., 1999; De Waele and Mapani, 2002) indicating that the granitoids exposed in the Copperbelt and surrounding areas are older than the Katangan sedimentary succession, i.e. Palaeoproterozoic (2.05–1.65 Ga), Mesoproterozoic (predominantly 1.05–1.0 Ga) or early Neoproterozoic, e.g. 0.88 Ga for the Nchanga granite which is unconformably overlain by the oldest Katangan sedimentary rocks.

Emerging in the 1930s, the syngenetic theory linked the deposition of metals to the deposition of host-sediments (Schneiderhöhn, 1931, 1932, 1937; Garlick, 1945, 1961b, 1967, 1989). Metals were sourced from continental erosion and transported in solution by rivers to the sedimentary depocentres. Ore sulphide precipitation occurred in reducing stagnant water under high bacterial activity and decomposition of organic matter. This hypothesis was based on: (1) the existence of sulphide zonal distribution parallel to the palaeo-shorelines inferred to mark marine transgression–regression events; (2) the coincidence between the polarity of the sulphide zonation and the sedimentary palaeocurrent directions. However, the lack of a systematic correlation between all transgressive/regressive events and lateral/vertical zonation of sulphides, and the discontinuity of the mineralisation within a single lithostratigraphic unit invalidated this model (e.g. Annels, 1974; Renfro, 1974; Sweeney and Binda, 1994).

Studies related to diagenetic processes in sedimentary rocks triggered the diagenetic model for the central African copper orebodies. Two sulphide generations were documented in the orebodies: (1) the earliest copper–(cobalt)-sulphide generation (hereafter sulphide I) grew during the deposition and the early diagenetic stage of the host-sediments; (2) the second copper–(cobalt)-sulphide generation was inferred to form during a large scale chemical reaction between the host-sediment interstitial water and a metal-bearing brine (Bartholomé, 1962, 1963, 1969, 1974; Bartholomé et al., 1972). However, the model does not address the origin of solutions, the primary source of metals, and the exact timing of mineralisation (early, late diagenesis). These unknowns led to a hydrothermal-diagenetic model linking the mineralizing fluids to late diagenetic hydrothermal fluids of undefined origin (Cluzel and Guilloux, 1986) or originating from mafic igneous rocks or rift related processes (Annels, 1974, 1979, 1989; Annels and Simmonds, 1984; Lefebvre, 1989; Unrug, 1988).

Cailteux et al. (1994) showed that stratiform copper–cobalt orebodies in Zambia and Congo are hosted in laterally correlative formations (Table 1). Therefore, the aim of this paper is to review data from both countries showing striking similarities between Congo-type and Zambia-type deposits, and allowing us to further constrain the mineralizing processes.

2. Geological setting

The Neoproterozoic Katangan belt forms a north-directed thrust-and-fold arc, called the "Lufilian Arc", located between the Congo and Kalahari cratons (Fig. 1). It is more than 150 km wide and stretches for 700 km from Mwinilunga in the west (e.g. Brock, 1961; Steven, 2000), to Kolwezi in the northwest, up to Luanshya (previously Roan Antelope) and Lonshi in the southeast of the belt (Fig. 2). It is commonly assumed that this copper

Table 1
Lithostratigraphy of the Katangan succession in Congo and Zambia (modified from François, 1974, 1995; Cailteux, 1994, 2003; maximum age of the Katangan based on SHRIMP U–Pb zircon dating by Armstrong et al., 1999)

	Group	Sub-group	Lithologies
±500 Ma	Kundelungu (prev. Upper Kundelungu) Ku	Plateaux Ku 3	Arkoses, conglomerates, sandstones, shales
		Kiubo Ku 2	Sandstones, carbonated siltstones or shales, limestones
		Kalule Ku 1	Ku 1.3: Carbonated siltstones and shales; grey to pink oolitic limestone at base ("Calcaire Rose Oolitique")
			Ku 1.2: Carbonated siltstones and shales; pink to grey dolomite at base ("Calcaire Rose")
±620 Ma			Ku 1.1 "Petit Conglomérat": glacial diamictite
	Nguba (prev. Lower Kundelungu) Ng	Monwezi Ng 2	Dolomitic sandstones, siltstones or shales
		Likasi Ng 1	Ng 1.3: Carbonated siltstones and shales
			Ng 1.2: Dolomites, limestones, dolomitic shales and siltstones
±750 Ma			Ng 1.1 "Grand Conglomérat": glacial diamictite

Congo: Group	Sub-group	Formation	Lithologies	Zambia: Lithologies	Formation	Sub-group
Roan	Mwashya R-4	Upper R-4.2	Shales, carbonaceous shales or sandstones	Dolomitic shales, grey to black carbonaceous shales, feldspathic sandstones		Mwashia
		Lower R-4.1	Dolomites, jasper beds, pyroclastics and hematite; local stratiform Cu–Co mineralisation			
	Dipeta R-3	R-3.4	Dolomites interbedded with argillaceous to	Dolomites interbedded with	Kanwangungu	Kirilabombwe
		R-3.3	dolomitic siltstones and feldspathic sandstones;	dolomitic shales; gabbroic bodies		RU 1 - RU 2 RL 3
		R-3.2	intrusive basic bodies			
		R.G.S. R-3.1	Dolomitic siltstones	Shales with grit	Kibalongo	
	Mines R-2	Kambove R-2.3	Laminitic, stromatolitic, talcose dolomites and dolomitic siltstones; local stratiform Cu–Co mineralisation	Dolomites or argillaceous dolomites; local stratiform Cu mineralisation	Chingola	Muscshi RL 4 - RL 6
		Dolomitic shale R-2.2	Dolomitic shales, carbonaceous shales, dolomites and occasional sandstones or arkoses	Arenites, argillites and dolomitic argillites; occasional dolomites	Pelito-arkosic	
			Dolomitic shales, sandy dolomite at top; stratiform Cu-Co (Upper Orebody)	at the base; main stratiform	Ore Shale	
		Kamoto R-2.1	R-2.1.3 "Roches Siliceuses Cellulaires": stromatolitic dolomite with interbedded siltstones; Cu–Co at top & base	Cu–Co mineralisation in the lower part (Ore Shale)		
			R-2.1.2: bedded dolomites with siltstones; silty dolomite in the lower part; stratiform Cu–Co (Lower Orebody)			
			R-2.1.1 "R.A.T. grises": dolomitic siltstone; Cu-Co at top			
	R.A.T. R-1	R-1.3	Pink-lilac, hematitic, chloritic–dolomitic massive siltstones	Conglomerates, coarse arkoses and argillaceous siltstones; occasional Cu–Co mineralisation	Mutonda	Mindola (Footwall) RL 7
		R-1.2	Pink to purple-grey, hematitic, chloritic siltstones; sandstones in the lower part; stromatolitic dolomite at top			
		R-1.1	purple-red, hematitic, slightly dolomitic bedded siltstones			
	base of the R.A.T. sequence unknown			Quartzites	Kafufya	
<900 Ma	Basal conglomerate			Pebble and cobble conglomerate	Chimfunsi	

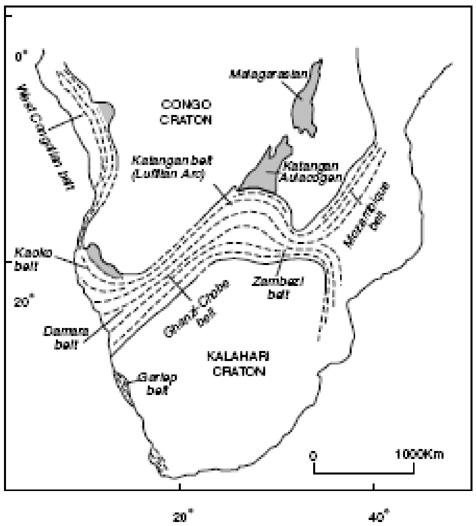

Fig. 1. Location of the central African Copperbelt between the Congo and Kalahari cratons.

metallogenic province is bounded by the Mwembeshi Dislocation Zone, but ongoing investigations (IGCP-302 and 450 projects) suggest that it possibly forms a vast copper metallogenic province extending into the Zambezi belt to the east, and linking southwestwards (Fig. 1) with the Kalahari Copperbelt of Botswana (Ghanzi-Chobe belt) and Namibia (Damara/Otavi belt).

The Katangan supracrustal sedimentary succession is ~5–10 km thick and commonly sub-divided into three major lithostratigraphic units (François, 1974, 1995): Roan, Nguba and Kundelungu Groups (Table 1). The Roan Group is made up of siliciclastic and carbonate sedimentary rocks (fluviatile and lacustrine sediments; Buffard, 1988; Cailteux, 1994; Cailteux et al., 1994), and volcanic and plutonic mafic rocks emplaced in a continental rift (Kampunzu et al., 2000 and references therein). The Nguba supracrustal assemblage is made up of siliciclastic and carbonate sedimentary rocks (François, 1974; Buffard, 1988) and includes mafic igneous rocks emplaced in a proto-oceanic rift similar to the Red Sea (Kampunzu et al., 1991, 1993; Manteka et al., 1985; Kapenda et al., 1998). Kundelungu sedimentary rocks represent syn- to post-orogenic sedimentary deposits (Kampunzu and Cailteux, 1999).

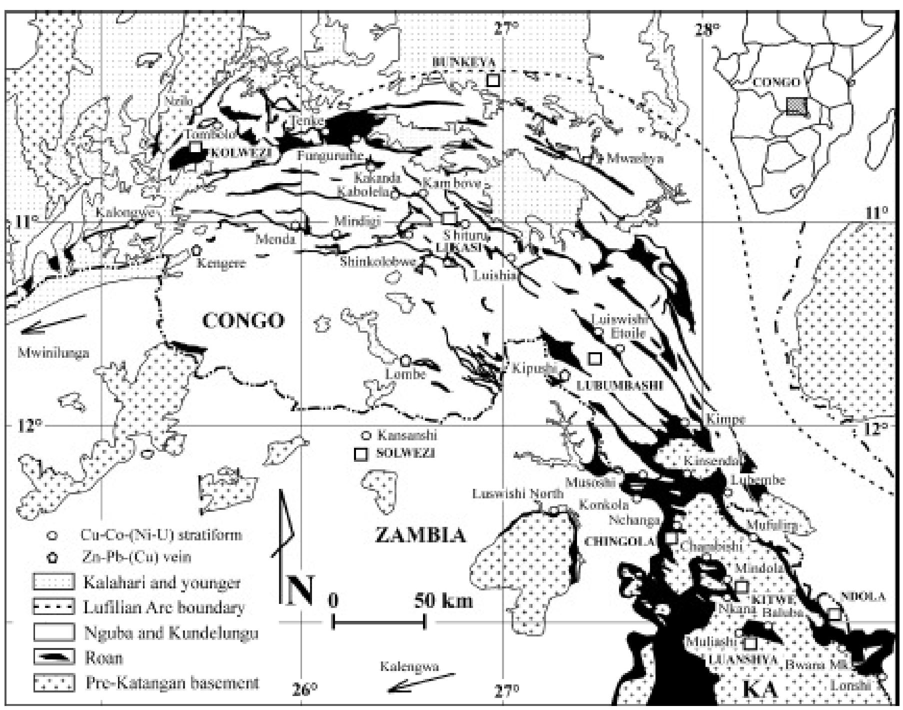

Fig. 2. Location of the main stratiform Cu-Co deposits in the central African Copperbelt (KA = Kafue Anticline); modified from François (1974) and Cailteux (1994).

The tabular-shaped Kundelungu is a continental clastic molasse sequence extending into the lower Palaeozoic (Kampunzu and Cailteux, 1999). The Katangan basin closed during the Lufilian Orogeny leading to the development of predominantly north-verging folds, thrusts and nappes. In Congo, all exposed Roan (except for the Nzilo basal conglomerate), Nguba and folded Kundelungu (excluding tabular Kundelungu) sedimentary rocks are part of allochthonous tectonic sheets. The Mwashya Subgroup rocks conformably overly the lowest Roan rocks (Cailteux et al., 1994), and are conformably overlain by the Grand Conglomérat (Table 1).

Grujenschi (1979) and Wendorff (2000a) interpreted occurrences of megabreccia in the Katangan succession as sedimentary syntectonic conglomerates (olistostromes), and Wendorff (2000b) further questioned the lithostratigraphic succession of the Roan Group. Although the existence of synorogenic sedimentary rocks in the Katangan is not a matter of debate (cf. Grujenschi, 1979), several claims in Wendorff (2000b) are not supported by available data (e.g. Cailteux et al., this volume; Kampunzu et al., this volume). In all cases, the debate on the lithostratigraphy of the Katangan is outside the objectives of this paper, and only the common lithostratigraphic position of the Mines Subgroup and related ore deposits is discussed further here below.

The stratiform Copperbelt copper–cobalt orebodies occur in the Roan Group (i.e. in Mines and Mwashya Subgroups; Table 1). The Roan Group sedimentary rocks display a regional lateral variation of facies between Zambia-type and Congo-type successions. In Zambia and SE Congo, deposits are mainly hosted in para-autochthonous siliciclastic rocks close to basement terrains. The main ore deposits define two parallel trends, north-east and south-west of the Kafue anticline (Fig. 2). The known deposits which lie off these two trends (e.g. Western province in Zambia) are assumed to be of smaller economic importance (Freeman, 1988a), although this could be a conclusion biased by inappropriate exploration coverage of this area.

The lowest Roan fluviatile sedimentary rocks rest unconformably on the pre-Katangan basement (Mendelsohn, 1961a; Binda and Mulgrew, 1974). In Congo, Cu–Co deposits and their host rocks define thrust sheets, nappes and klippen formed during the Lufilian Orogeny (Demesmaeker et al., 1963; Cailteux and Kampunzu, 1995; Kampunzu and Cailteux, 1999). The dominant lithological units are dolomites and dolomitic shales (Oosterbosch, 1962; Demesmaeker et al., 1963; François, 1974, 1987; Cailteux, 1994).

The lowest formations of the Roan Group (R.A.T.—"Roches Argilo-Talqueuses"—and Mindola Subgroups; Table 1) were deposited in an oxic environment. In Zambia, the Mindola Subgroup includes (Binda, 1994; Cailteux et al., 1994; Tshiauka et al., 1995): a scree-type boulder conglomerate at the base (Chimfunsi Formation), followed by aeolian quartzites (Kafufya Formation) and by immature braided stream/alluvial fan conglomerates, arkoses and upward-fining sandstone sequences (Mutonda Formation). In Congo, the base of the R.A.T. Subgroup is unknown (François, 1974), but a boulder conglomerate, probably correlative of the Chimfunsi Formation, occurs at Nzilo above the Kibaran basement. R.A.T. sedimentary rocks, laterally correlative of the Mutonda Formation (Cailteux et al., 1994), include red chlorite-rich dolomitic siltstones, dolomitic fine-grained sandstones, silty dolostones and dolomitic silty chloritites (Oosterbosch, 1950; Katekesha, 1975; Cailteux, 1978a, 1983, 1994).

Wendorff (2000b) claims that Red and Grey R.A.T. are syn-orogenic sedimentary rocks younger than the Roan Group and deposited in the Katangan foreland basin after the deposition of the Nguba Group. However, field observations and geochemical data invalidate this interpretation (Cailteux et al., this volume; Kampunzu et al., this volume). Furthermore, the same author suggested that the Nzilo conglomerate is part of the Mwashya Subgroup, but there is no field evidence supporting this interpretation (e.g. Byamungu et al., 1979; Madi, 1985).

Musoshi (Zambia) and Mines (Congo) Subgroups (Table 2) represent a transgressive succession deposited in a reducing evaporitic environment. They include a succession of arenites, silty-sandy argillites and shales exposed north of the Kafue "Anticline" (Zambia), dolomitic shales and dolomites in Congo and south of the Kafue "Anticline" in Zambia (Bartholomé et al., 1972; Annels, 1974; Binda and Mulgrew, 1974; Cailteux, 1978a, 1994; Cailteux et al., 1994; Tshiauka et al., 1995). A carbonate unit marks the top of the laterally correlative mineralised successions in Congo and Zambia. The copper–cobalt orebodies occur in the lower part of these successions and the stratiform mineralisation was deposited before the Lufilian compressional tectonics both in Congo and Zambia, as shown by folds and thrusts affecting the orebodies (Garlick, 1940; Reynolds, 1959; Mendelsohn, 1961c; Demesmaeker et al., 1963; François, 1973; Katekesha, 1975; Cailteux, 1983; Cailteux and Kampunzu, 1995).

The laterally correlative Kirilabombwe (Zambia) and Dipeta (Congo) Subgroups display strong similarities, e.g. the lithological succession includes arkoses, conglomerates, siltstones, dolomitic shales, dolomites, and these lithologies show a similar succession. The Mwashya Subgroup is characterized by platform carbonates in the Lower Mwashya, grading to more open marine dolomitic shales, black shales or sandstones in the Upper Mwashya. Gabbros intruding the Upper Roan/Dipeta formations (but not the Mwashya Subgroup) and mafic lavas and pyroclastic rocks in the Lower Mwashya belong to a single syn-Lower Mwashya igneous event (Kampunzu et al., 2000 and references therein) dated at 760 ± 5 Ma by U–Pb SHRIMP technique (Key et al., 2001). The upper Mwashya is overlain by a glacial diamictite, called "Grand Conglomérat" which starts the Nguba succession (Cahen, 1954; Binda and Van Eden, 1972).

Table 2
Lithostratigraphy of the Mines Subgroup in Congo (modified from François (1987) and Cailteux (1994))

Sub-group	Formation	Member	Lithology	
Mines R-2	Kambove R-2.3 (up to 190 m)	Upper R-2.3.2	White to pink massive dolomites and more or less talcose finely bedded dolomites, with interbedded grey to pink-red chloritic–dolomitic siltstones, occasional evaporitic-type collapse breccias and intraformational conglomerates	
			More or less carbonaceous, massive dolomites with occasional stromatolites,	
			more or less talcose finely bedded dolomites with interbedded chloritic–dolomitic siltstones, occasional evaporitic-type collapse breccias and intraformational conglomerates	Third Orebody (lenses)
			Pink-brown to white massive dolomite	
		Lower R-2.3.1	More or less carbonaceous, talcose, massive or finely bedded dolomites, with occasional oolitic or cryptoalgal beds	
			More or less carbonaceous laminitic dolomites with tabular stromatolites, talcose to the top	
			More or less carbonaceous, massive, stromatolitic dolomites with interbedded dolomitic shales and laminitic dolomites	
	Shales dolomitic R-2.2 (up to 110 m)	S.D.-3b	Black carbonaceous weakly dolomitic shale	
		S.D.-3a	Highly dolomitic shales, with occasional stromatolitic dolomite bed at top or at base	
		S.D.-2d	Black carbonaceous weakly dolomitic shale	
		S.D.-2c	Highly dolomitic shales; occasional black carbonaceous shale at base	
		S.D.-2b	Dolomitic shales, with frequent stromatolitic dolomite bed at base	
		S.D.-2a	Black carbonaceous weakly dolomitic shale	
		S.D.-1b (B.O.M.Z.)	Silty and chloritic dolomite, coarse crystalline dolomite and dolomitic shales, with nodules and concretions pseudomorph after anhydrite	Upper Orebody
		S.D.-1a (S.D.B.)	Dolomitic shales, with lenticular beds and nodules pseudomorph after anhydrite	
	Kamoto R-2.1 (up to 50 m)	R.S.C.	Massive, stromatolitic dolomites, with interbedded dolomitic siltstones	
		R.S.F.	Siliceous finely bedded dolomites with laminitic stromatolites; interbedded dolomitic siltstones or shales	Lower Orebody
		D.Strat.	More or less silty and chloritic stratified dolomites	
		R.A.T. grises	Grey chloritic–dolomitic massive siltstone (up to 10 m)	

3. Lithostratigraphic control of copper–cobalt ores

Major primary deposits and most primary copper occurrences are stratigraphically controlled (Tables 1, 2), i.e. they occur in the Kamoto Dolomite and Dolomitic Shales Formations of the Mines Subgroup in Congo (Oosterbosch, 1962; Cailteux, 1994 and references therein), and in lateral correlative units known as the Ore Shale Formation (Binda and Mulgrew, 1974; Cailteux et al., 1994) at the base of the Musoshi Subgroup in Zambia. Within these lithostratigraphic units, the orebodies extend for hundreds of metres (e.g. Kakanda-Nord; Fig. 3) to several kilometres (e.g. Dikuluwe-Mashamba at Kolwezi; Luanshya in Zambia) along strike, except where they are interrupted by compressional structures related to the Lufilian orogeny (Demesmaeker et al., 1963; Kampunzu and Cailteux, 1999). The lateral variation of sulphides in the orebodies shows copper-rich zones grading into copper-poor zones and to pyritic-barren zones; e.g. Kambove-Ouest (Cailteux, 1983, 1986, 1994) and Nchanga (McKinon and Smit, 1961).

Some Cu–(few Co) primary sulphide mineralisations occur in the Mwashya Subgroup in Congo, and also are stratigraphically controlled in dolomites of the Lower Mwashya.

3.1. Mines Subgroup Congo-type deposits

The Congo-type stratiform deposits stretch from Kolwezi up to Kimpe (Fig. 2) and are generally characterized

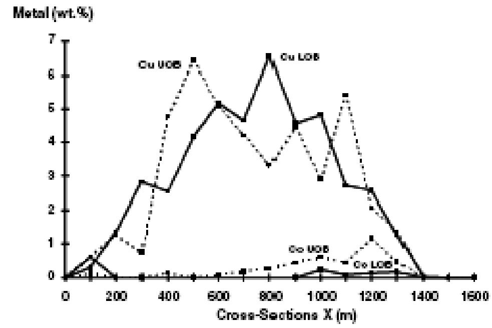

Fig. 3. Kakanda-Nord: distribution of Cu and Co average concentrations on cross-sections from X: 0 to X: 1600 (LOB = lower orebody; UOB = upper orebody).

by two major Cu–Co orebodies, the "lower" and "upper" orebodies, totalling ~15–55 m cumulative thickness (average: ~20–25 m). The mineralisation is hosted in a transgressive supratidal to subtidal sedimentary sequence deposited under quiet, shallow-water conditions (Bartholomé et al., 1972; Cailteux, 1978a, 1983, 1994). The host rocks contain blebs, nodules and lenticular beds of dolomite–quartz pseudomorphs after anhydrite and gypsum, and high contents of Mg, Ba, Sr, Li, B, Br can be linked to the deposition of sediments under saline evaporitic conditions (Bartholomé et al., 1972; Katekesha, 1975; Cailteux, 1978a, 1983, 1994; Moine et al., 1986).

The lower orebody host-rocks include (Table 2): (1) a massive chloritic–dolomitic siltite known as Grey R.A.T. ("Roches Argilo-Talqueuses"); (2) a fine-grained stratified dolostone (D.Strat. "Dolomie Stratifiée"); (3) silicified-stromatolitic-dolomites forming laminites alternating with thin chloritic–dolomitic silty beds (R.S.F. "Roches Siliceuses Feuilletées"). The Upper Orebody host-rocks include (Table 2): (1) the basal Dolomitic Shales (S.D.B., "Shales Dolomitiques de Base" also called S.D.1a); (2) an overlying coarse grained impure dolostone (B.O.M.Z., "Black Ore Mineralised Zone" also called S.D.1b) which is sometimes missing in the succession (e.g. in the Kambove area). A generally "barren" reef-type stromatolitic dolomite (R.S.C., "Roches Siliceuses Cellulaires") occurs between the two orebodies. Ores are known on 0.4–1.0 m thickness along the contact between this reef dolomite and both lower and upper orebodies. The chloritic-silty-dolomitic lenses or layers locally interbedded within the R.S.C. are also mineralised (e.g. Kamoto). In some deposits (e.g. Kambove-Ouest), the primary stratiform mineralisation extends to the overlying carbonaceous dolomitic shales S.D.2a, up to the base of the S.D.2b. The organic matter content is variable, generally low, although local high contents have led to the development of black shales and dolomites in R.S.F.-R.S.C.-S.D.B units (Cailteux, 1983).

The Congo-type mineralised succession is very regular along strike (Fig. 2), showing the same lithological succession for >350 km, from Kolwezi (Demesmaeker et al., 1963; François, 1973; Katekesha, 1975), to Tenke-Fungurume (Oosterbosch, 1950, 1951), Kambove-Kakanda (Cailteux, 1978a, 1983), Kabolela (Lefebvre, 1976a,b), Etoile (Lefebvre and Cailteux, 1975) and Lubembe (Lefebvre and Tshiauka, 1986; Tshiauka et al., 1995). However, there is a clear across-strike lithofacies variation marking a progressive evolution from more near-shore (north) to more reefal (south) environments (François, 1973, 1974; Lefebvre, 1979; Cailteux, 1978, 1983, 1994). This palaeoenvironmental variation seems to correlate with different copper–cobalt grades in the rocks (François, 1973, 1974, and details below). The northern (present coordinates) near-shore sequences ("Long" and "Kilamusembu" facies) are characterized by the absence of stromatolites, the occurrence of dolomites and arenites in the Dolomitic Shales Formation and of arenites in the Kambove Formation. In these two sequences, the lithostratigraphic units usually hosting the orebodies are barren or poorly mineralised (e.g. Dipeta Syncline between Tenke and Fungurume), except in the Tenke deposit. The Kilamusembu facies occurs only in the Kolwezi area and represents a transitional facies between Long and Musonoï facies. The southern sequences ("Musonoï" and "Kalumbwe" facies) are marked by: (a) clasts of stromatolites; (b) stromatolites in R.S.C.; (c) lack of arenites in Dolomitic Shales and Kambove Formations. There are no dolomites in the Kalumbwe facies Dolomitic Shales Formation (e.g. Kakanda-Nord). This sequence hosts the most important copper–cobalt deposits (e.g. Kamoto, Fungurume), with only a few barren or poorly mineralised zones. The southernmost reef sequence ("Menda" and "Luishia" facies) is marked by algal bioherms in R.S.C. and in the Kambove Formation. The lithostratigraphic units usually hosting the orebodies are barren or poorly to well mineralised (e.g. Kambove-Ouest, Luishia, Luiswishi).

Sub-economic orebodies (generally <1 wt.% Cu) and small economic deposits (locally >2 wt.% Cu) occur in dark-grey to black carbonaceous metapelites forming the S.D.2d and 3b (Figs. 4 and 5; Table 2). However, the metals in these units are strictly bound to thin organic matter-rich horizons indicating deposition under strong reducing conditions.

Other economic to sub-economic Cu–Co mineralisations in the Menda and Luishia facies (e.g. Kambove-Ouest, Luishia, Luiswishi) are hosted stratigraphically higher up, in the Kambove Formation (upper part of the Mines Subgroup), i.e. 60–100 m above the classical upper orebody described above (Tables 1, 2; Figs. 4, 5). For clarity, the small orebodies in the Kambove Formation will be called globally the third Congo-type orebody in this paper. The stratiform disseminated sulphides of this third orebody (4–20 m thick, 10–100 m long bodies) are hosted in tidal and reef lithologies similar to the host rocks in the lower and upper orebodies (Cailteux, 1978b, 1986, 1994). However, the host rocks are this time part of a regressive sequence. A major point from these data is that Cu–Co

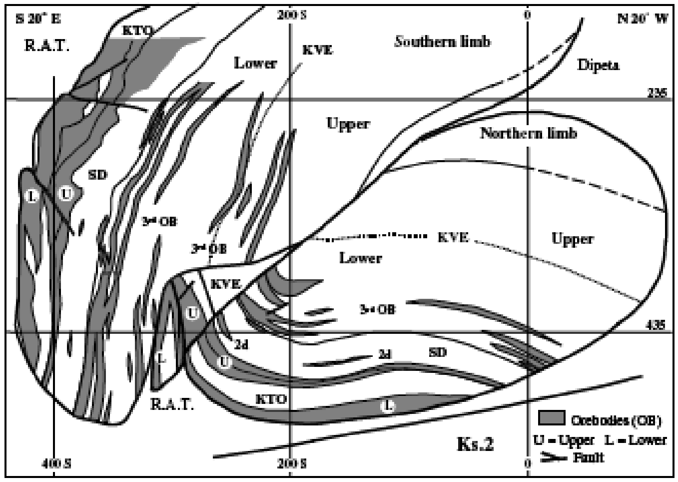

Fig. 4. Cross-section X: 90 E through the Kambove-Ouest deposit and Roan breccia below the oxidized zone (modified from Cailteux, 1983); KTO = Kamoto Formation, SD = Dolomitic Shale Formation, KVE = Kambove Formation; R.A.T. = Roches Argilo-Talqueuses.

ore deposits in the central Africa Copperbelt are closely linked to tidal and reef sedimentation.

3.2. Musoshi Subgroup Zambia-type deposits

The Zambia-type deposits are characterized by one or several orebodies, called "Ore Shale", and hosted in the Ore Shale Formation (Darnley, 1960; Mendelsohn, 1961c; Garlick, 1961b; Garlick and Fleischer, 1972; Van Eden and Binda, 1972; Cailteux, 1973; Annels, 1974; Binda and Mulgrew, 1974; Clemmey, 1974; Van Eden, 1974; Cailteux and Lefebvre, 1975). The Ore Shale Formation is a sedimentary unit ranging in lithology from quartzo-feldspathic wacke (Mufulira) to siltstone (e.g. Konkola, Chambishi), to finely laminated argillite (e.g. Nkana) and to shaley or siliceous dolomite (e.g. Baluba, Muliashi South) (Binda and Mulgrew, 1974; Binda, 1994). The Musoshi Subgroup includes also lithologies (e.g. Nchanga, Nkana, Mufulira, Baluba, Mindola) transitional to those of the Congo-type lower and upper orebodies (Cailteux et al., 1994; Binda, 1997). The lack of a reef sedimentary package in the Zambian orebody marks the predominantly clastic sedimentation in the Zambia-type Roan sequence. However, several reef occurrences were described or mentioned (e.g. Mufulira, Pitanda/NW and Kitwe/SE sides of the Chambishi-Nkana basin, Luanshya; Malan, 1964; Clemmey, 1974). The Ore Shale Formation is marked by evaporitic conditions, as shown by preserved blebs and beds of anhydrite (Brandt et al., 1961; Annels, 1974; Clemmey, 1974), and by tidal flat/subtidal regressive and transgressive sequences grading into stromatolitic carbonates (e.g. Kitwe; Clemmey, 1974).

The Ore Shale includes one (e.g. Musoshi-Konkola, Nkana; Jordaan, 1961; Schwellnus, 1961; Cailteux, 1973) or several orebodies separated by barren (<1 wt.% Cu) or low grade (1–1.5 wt.% Cu) mineralised beds (e.g. Nchanga and Nchanga-West orebodies; Lower and Upper Orebodies at Luanshya; A, B, C Orebodies at Mufulira and Mimbula; Brandt et al., 1961; McKinon and Smit, 1961; Mendelsohn, 1961d; Smit, 1961; Freeman, 1988b). The Ore Shale cumulative thickness is 5–50 m (average: 20–25 m), i.e. of the same order as the cumulative thickness of orebodies in the Congo-type deposits. Sulphides occur along foresets of cross-bedding, within troughs of ripples and along shale laminae; erosional channels interrupt mineralised beds; ore and its host-rocks display sedimentary deformation structures such as slumping or compaction cracks (Garlick, 1961b). Evaporitic conditions are supported by preserved blebs and beds of anhydrite (Brandt et al., 1961; Annels, 1974). Clemmey (1974) documented a strong relation between mineralisation trends and the sedimentary context at Kitwe: (1) copper grades are highest toward the inferred palaeo-land and decrease away from it; (2) the alignment of copper grades is in shoots parallel to deducted ebb and flood tidal directions; (3) copper grades are controlled by facies distribution.

Lenticular quartzites, feldspathic quartzites, and dolomitic argillite in the hangingwall host a few small copper mineralisations forming the topmost orebodies, including The Feldspathic Quartzite (T.F.Q.) at N'changa and the weakly mineralised Glassy Quartzite at Mufulira (Binda and Mulgrew, 1974). These may be potential Zambian correlatives of the third orebody hosted in the Kambove Formation in the Congo-type deposits.

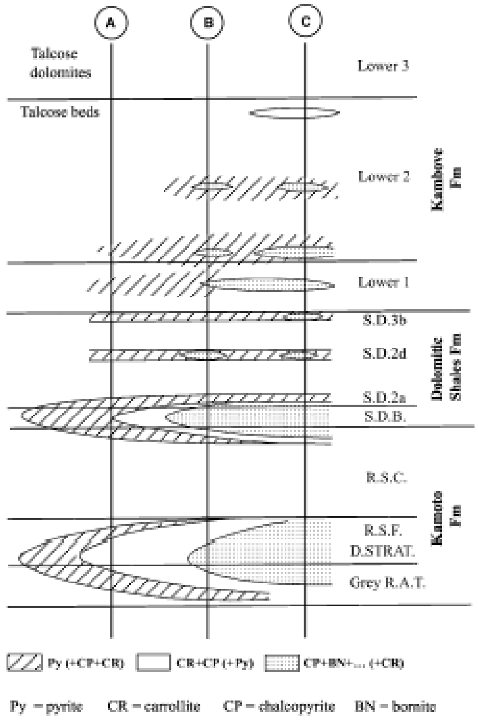

Fig. 5. Schematic reconstruction of the Fe–Cu–Co sulphide distribution in the Kambove area (Cailteux, 1994). (A) Kw-236 low-grade deposit; (B) and (C) northern and southern folds, respectively, Kambove-Ouest deposit. The distances between A–B and B–C profiles are both ~500 m.

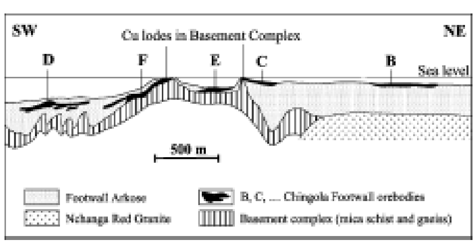

Fig. 6. Chingola B, C, D, E, F footwall orebodies (Binda, 1997).

Several ore occurrences or deposits lie below the Ore Shale (Fig. 6), including four major orebodies at Kinsenda (Ngoyi and Dejonghe, 1997), three at Lubembe (Lefebvre, 1989; Tshiauka, 2001), several orebodies in Nchanga (Voet and Freeman, 1972; Freeman, 1988b), minor occurrences at Chambishi (Garlick, 1961c), one orebody at Nkana (Jordaan, 1961), three mineralised lenses at Chibuluma (Winfield, 1961) and Muliashi-South in the Luanshya district (Van Eden and Binda, 1972). These are not in the classical lithostratigraphic position of orebodies in the Copperbelt since these stratiform orebodies occur in arkoses of the commonly barren siliciclastic Mutonda Formation.

3.3. Mwashya Subgroup deposits

The Mwashya Subgroup is exposed for several hundred kilometres along major Lufilian thrust faults between Kolwezi to the west and Kimpe to the southeast (Fig. 1). Several copper deposits and sub-economic occurrences (<1.0 wt.% Cu) were recorded in the Lower Mwashya: e.g. Shituru and Mulungwishi-Kampina (Likasi district), Kipoï (Luishia district), Kifumashi and Kasonta (Lubumbashi area) (François, 1974; Gécamines, unpublished data).

The Shituru deposit, located 1 km away of the Likasi Shituru plant (Fig. 1), is the only mined deposit hosted in the Lower Mwashya. It occurs on the southern flank of an anticline faulted along the fold axial plane. Mineralisation forms two stratiform orebodies (upper and lower) with high grades in the supergene zone (≈10.5 wt.% Cu and up to 2.0 wt.% Co; François, 1974; Lefebvre, 1974), and with lower grades (⩽2 wt.% Cu and ⩽0.1 wt.% Co) at the deeper level (>80 m depth) (Lefebvre, 1974). Most ores are hosted in dolomitic laminites and dolomitic shales, lithologically similar to R.S.F./D.Strat-type and S.D.-type rocks of the Mines Subgroup, and interbedded with sub-economic (<1.0 wt.% Cu) stromatolitic massive dolomite (Lefebvre, 1974). No direct link has been found between the pyroclastic rocks interbedded in the Lower Mwashya and this copper mineralization (Lefebvre, 1974).

4. Copper–cobalt distribution in the central Africa Copperbelt

Based on present day mined out production, ore reserves and resource evaluation using cut off grades of ⩾1 wt.% Cu, the economic orebodies host 82.2 Mt copper and 1.4 Mt cobalt in Zambia-type deposits, against 58.0 Mt copper and 4.6 Mt cobalt in Congo-type deposits. This adds up to ~140 Mt copper and 6 Mt cobalt for the whole central African Copperbelt (Freeman, 1988a,b; Gécamines, unpublished data). Therefore, the Zambia-type orebodies contain 59% of the copper whereas the Congo-type orebodies host 77% of the cobalt in the Copperbelt. The known ore deposits in Western Zambia represent less than 1% of the total evaluated copper. The overall Co:Cu ratio is 1:57 in Zambia-type against 1:13 in Congo-type deposits, although cobalt-rich deposits reach Co:Cu ratios of 1:15 in Zambia-type and 3:1 in Congo-type orebodies. Geochemical studies (Kampunzu et al., unpublished work) indicate that the total amount of copper and cobalt contained in the Katangan economic orebodies represents ±8% and 0.8%, respectively, of the total (i.e. 1850 Mt copper and 750 Mt cobalt, respectively) metal contained in Roan sedimentary rocks.

The distribution of copper and cobalt deposits is related to the regional tectonic control of the distribution of the

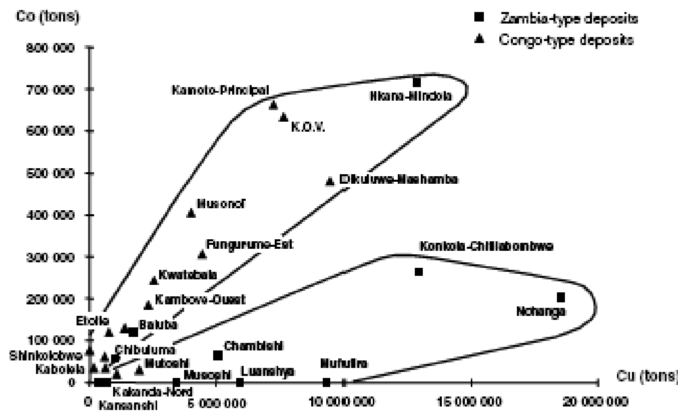

Fig. 7. Distribution of the Congo–Zambia Copperbelt Mines/Musoshi Subgroups deposits according to their Cu and Co tonnages.

Mines Subgroup and lateral correlative units along the Lufilian Arc (François and Oosterbosch, 1968; François, 1973, 1974). The Long and Kilamusembu facies exposed between Kolwezi and Tenke contain 26% and 19% of Katangan belt copper and cobalt resources, respectively; they are marked by low copper grades (1.0–2.0 wt.% Cu) and relatively low cobalt contents (0.1–0.4 wt.% Co). The Musonoi and Kalumbwe facies exposed between Kolwezi and Kakanda-Fungurume host copper-rich (>2.0 wt.% Cu) and cobalt-poor to cobalt-rich (<0.1–0.5 wt.% Co) ores, representing 56% and 61% of Katangan belt copper and cobalt resources, respectively. The southern Menda and Luishia facies (18% copper and 20% cobalt resources) is exposed from Kalongwe to Etoile and host copper- and cobalt-rich (>2.0 wt.% Cu and 0.4–0.6 wt.% Co) ores. Substantial nickel (from several hundred ppm up to ⩾0.5 wt.% Ni) is associated with cobalt in the Menda and Luishia facies, forming Ni–Co sulphide deposits (e.g. Shinkolobwe). Between Lupoto and Lubembe, the Luishia facies host cobalt-poor (<0.1–0.4 wt.% Co) orebodies.

In Zambia, cobaltiferous deposits occur southwest of the Kafue Anticline (Fig. 2), e.g. Konkola-Chililabombwe, Nchanga, Chambishi Southeast, Chibuluma (West of Nkana), Luanshya and Baluba deposits (Annels et al., 1983; Annels and Simmonds, 1984; Freeman, 1988b). Cobalt contents are generally between 0.1–0.2 wt.% Co (e.g. Chambishi, Nkana), with local higher values (e.g. up to 0.44 wt.% Co at Nchanga), matching the concentration range reported in Congo. There is almost no cobalt in the copper deposits northeast of the Kafue Anticline, e.g. Kinsenda (Congo), Mufulira, Bwana Mkubwa (Zambia). This pattern compares to that documented in Congo where the richest cobalt deposits occur along the southern fringe of the Copperbelt.

The Co:Cu ratio defines two geochemical groups of stratiform copper deposits in the central African Copperbelt (Fig. 7): (1) the first group represents cobalt-poor copper deposits marked by low Co:Cu ratio (0–0.02). This group includes most Zambia-type copper deposits and a few Congo-type deposits (e.g. Mutoshi in the Kolwezi area, Kakanda-Nord, Kalengwa in western Zambia); (2) the second group represents cobalt-rich copper deposits marked by high Co:Cu ratio (0.02–2.80), including most Congo-type deposits and some deposits in Zambia (e.g. Nkana-Mindola, Nchanga, Baluba). The highest Co grades within the total resources in Zambia (Co:Cu = 0.05–0.07) occur in the Baluba, Nkana-Mindola, Chibuluma deposits (Freeman, 1988b), which show transitional lithofacies between Zambia-type and Congo-type sedimentary sequences. Local high grades are documented in the Nchanga deposit. The Mwashya Subgroup Shituru deposit is part of the low Co:Cu ratio (0.01) deposits.

5. Metal and sulphide distribution within the orebodies

Most Copperbelt deposits display vertical and lateral zoning of disseminated copper sulphides. In Zambia-type deposits, the vertical zoning starts with chalcocite–digenite–bornite at the bottom, followed by bornite–chalcopyrite and chalcopyrite-dominant zones, and pyrite at the top (e.g. Chambishi, Chibuluma, Baluba, Nchanga, Musoshi; Garlick, 1961c; Lee-Potter, 1961; McKinon and Smit, 1961; Cailteux, 1973, 1974). A similar trend marks some Congo-type deposits. For example, the Kamoto deposit is characterized by chalcocite–digenite–bornite in the lower orebody (Grey R.A.T., D.Strat., R.S.F.) and in S.D.B., chalcopyrite and minor bornite in B.O.M.Z., chalcopyrite–pyrite in S.D.2a and pyrite in S.D.2b (Oosterbosch, 1962; Bartholomé, 1962, 1963, 1969). Outside the orebodies, pyrite is common and coexists sometimes with a few chalcopyrite grains.

Etoile and Kambove-Ouest deposits (Congo) display a different sulphide zonation in the same lithostratigraphic units. At Etoile, two sequences from chalcocite to bornite and chalcopyrite were observed, one from Grey R.A.T. to D.Strat., the other from R.S.F. to S.D.B. (Lefebvre and Cailteux, 1975). At Kambove-Ouest (Cailteux, 1983, 1986), chalcopyrite is dominant at the base (Grey R.A.T.) and at the top of S.D.B, whereas a chalcocite–digenite–bornite zone occurs in the middle (D.Strat., R.S.F., base of S.D.B.). This illustrates the variability of the sulphide zonation within the same sedimentary units, implying that this zonation is not controlled by the lithological characteristics of the host rock.

The third "orebody" (Kambove Formation) is hosted in dolomitic shales and dolomitic laminites at Kambove-Ouest, with a remarkable decimetric to metric vertical zoning marked by the recurrence of pyrite–chalcopyrite–bornite–chalcopyrite–pyrite ores (Fig. 8). Carrollite (cobalt-copper sulphide) is irregularly distributed in the orebodies. It is associated with chalcopyrite and pyrite in copper-poor zones (e.g. Kambove-Ouest, Chibuluma, Nkana). In the Kambove-Ouest deposit, a 0.5–1.5-m thick carrollite–chalcopyrite orebody frequently occurs in the pyritic Grey R.A.T. below the base of the lower orebody. Centimetric grains of carrollite occur in the poorly mineralised R.S.C. and define orebodies in talcose dolomites of the Kambove Formation (Figs. 4, 5).

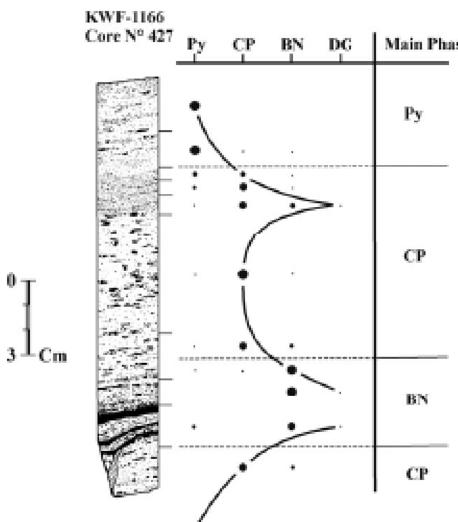

Fig. 8. Decimetric sulphide zoning in the Kambove Formation (third orebody) at Kambove-Ouest (Cailteux, 1986). Minor carrollite is associated with the copper sulphides. Py = pyrite; CP = chalcopyrite; BN = bornite; DG = digenite.

The lower orebody sulphide mineralisation in the Lower Mwashya Shituru deposit includes disseminated pyrite, chalcopyrite, bornite, minor carrollite/linnaeite and supergene copper sulphide (digenite, chalcocite) associations, similar to those of the Mines Subgroup orebodies (Lefebvre, 1974). However, there is no zoning in these sulphides. The upper orebody contains finely disseminated pyrite in the unweathered zone.

In the Congo-type Mines Subgroup deposits, the highest Co:Cu ratio occurs in the upper part of the orebodies, and shows local positive anomalies in the hangingwall (Fig. 9a and b). In the Zambia-type sequence, linnaeite and carrollite occur in the Ore Shale, mainly within its lower part (e.g. Nchanga, Chambishi, Mindola, Nkana, Chibuluma, Muliashi, Baluba; Mendelsohn, 1961c; Annels et al., 1983; Annels and Simmonds, 1984; Fig. 9d).

Cobalt or cobalt–nickel disseminated sulphides in copper-rich stratiform ores from both Congo- and Zambia-type deposits include mostly cattierite and cobaltite at Kinsenda and Luiswishi (Dejonghe, 1995; Ngoyi and Dejonghe, 1997; Loris et al., 1997), siegenite at Kambove-Ouest and Luiswishi (Cailteux, 1997; Loris et al., 1997), Co-pentlandite at Chambishi (Annels et al., 1983; Annels and Simmonds, 1984). Other deposits contain nickel/cobalt-rich and copper-poor stratiform orebodies, i.e. Ni-cattierite, Co-vaesite and siegenite in Shinkolobwe and Swambo (Derriks and Vaes, 1956; Derriks and Oosterbosch, 1958; Oosterbosch, 1962), siegenite and violarite in Kalumbila (Kabompo Dome; Steven and Armstrong, 2003).

Co, Ni, Cu diagrams show variable inter-element ratios in the orebodies and the hangingwall (Fig. 9a–d). Microprobe analyses showed that nickel content is <1 wt.% in sulphides, i.e. in carrollite and cattierite, chalcopyrite, chalcocite and Co-pyrite from Kamoto, Kambove-Ouest, Shinkolobwe, Musoshi-Konkola, Baluba, Chibuluma, Chambishi (Bartholomé et al., 1971; Cailteux, 1974, 1997; Craig and Vaughan, 1979; Annels et al., 1983; Sweeney et al., 1986). Sulphides from some deposits (e.g. Kamoya Sud-II in the Kambove area) contain several hundred, up to 1000 ppm Ni in the oxide ores, but Ni:Co ratio remain very low (⩽0.01). Microprobe analyses identified a complete solid solution between pyrite (FeS_2), cattierite (CoS_2) and vaesite (NiS_2) (Loris, 1996; Loris et al., 2002). Sulphides of the linnaeite group were also documented, with chemical compositions indicating siegenite, linnaeite, carrollite or polydymite. In the richest cobalt deposits (e.g. Shinkolobwe, Swambo), Ni:Co ratios is higher (e.g. 1:4) since nickel concentration reaches 0.5 wt.% in a disseminated ore containing Ni-cattierite thiospinel, siegenite, vaesite in addition to pyrite and chalcopyrite (Derriks and Vaes, 1956; Derriks and Oosterbosch, 1958). Linnaeite (Co_3S_4)-carrollite (Co_2CuS_4) thiospinel solid solutions contain significant amounts of Ni and Fe. Zambian thiospinels yielded 0.45–2.53 wt.% Ni (Annels et al., 1983), whereas higher values (11.4–12.2 wt.% Ni) were reported at Shinkolobwe (Craig and Vaughan, 1979). These data indicate

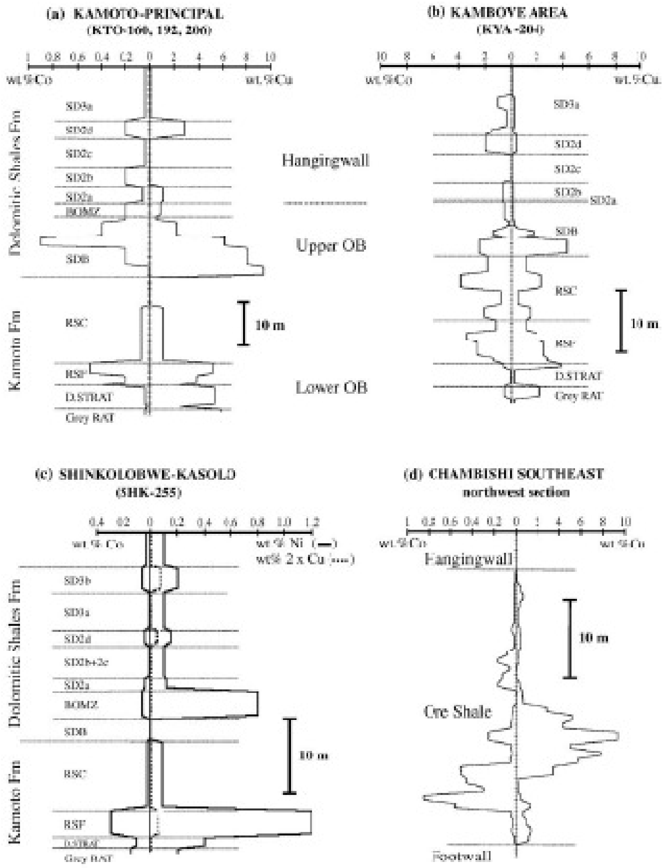

Fig. 9. Cu and Co distribution diagrams in the orebodies and hangingwall of representative Copperbelt ore deposits (data from Oosterbosch, 1962 for Kamoto and Shinkolobwe and from Annels and Simmonds 1984 for Chambishi Southeast).

that nickel is closely linked to primary Cu–Co ore in the central African Copperbelt.

Since 1903, gold, platinum–palladium and silver were mined from Congo-type Cu–Co stratiform deposits, i.e. Mutoshi (formerly Ruwe), Musonoi (Kolwezi area) and Shinkolobwe; their concentration in ores from the oxidized zone reached 26 g/t Au, 36 g/t Pd, 10 g/t Pt (du Trieu de Terdonck, 1956; Jedwab, 1997). These precious metals occur in the lower orebody (mainly in R.S.F.) and form pure nuggets and alloys (involving Cu and/or Se) or are included in oxides (e.g. palladinite, Fe-Co–Ni–Cu–Mn hydroxides), As/Se/Te metallic compounds (e.g. costerboschite, mocheite, trogtalite) or sulphides (e.g. linnaeites, Se–As sulphides). Sub-economic occurrences were recorded in oxide ores from a few Cu–Co deposits, e.g. gold at Kalongwe, Fungurume, Kamoya (Kambove area), Likasi (du Trieu de Terdonck, 1956), Pd-Au at Mindigi (Jedwab, 1997). The grades in these occurrences may reach 0.3 g/t Au, 2.9 g/t Ag and 0.3–0.6 g/t Pt-Pd. Platinum and palladium are generally hosted in heterogenites. In Zambia, Au also occurs in Cu–Co ores since it is recovered from electrolytic Cu refining.

6. Ore petrology

6.1. Sulphide parageneses

Parageneses of the stratiform disseminated sulphides are well documented both in Congo- and Zambia-types deposits, e.g. at Kamoto-Principal (Bartholomé, 1962, 1963; Bartholomé et al., 1971, 1972; Dimanche, 1974), Musoshi

(Cailteux, 1973, 1974), Kambove-Ouest (Cailteux, 1983, 1986), Luiswishi (Loris, 1996; Loris et al., 2002) and Kinsenda (Ngoyi and Dejonghe, 1997).

Framboidal-pyrite (pyrite-I) grains (Fig. 10a) occur mainly within zones adjacent to the orebodies (below, above, and laterally). Sometimes, chalcopyrite (-I) or bornite (-I) form the core of this early pyrite (Cailteux, 1974). Microprobe analyses indicated the presence of copper in framboidal pyrite-I and revealed cobalt–nickel rich pyrite (-II) forming the outer rims of pyrite-I grains, e.g. at Kamoto (Bartholomé et al., 1971), Musoshi (Cailteux, 1974) and Kinsenda (Ngoyi and Dejonghe, 1997). Parageneses with pyrite-I—(Co,Ni) pyrite-II (bravoite)—pyrite-III concentric zones were reported in the Luiswishi deposit (Loris, 1996; Loris et al., 2002). Framboidal and small isolated grains of pyrite (I, II, III) are included in diagenetic quartz and dolomite (Fig. 10b), e.g. at Kamoto (Bartholomé et al., 1971) and Kambove-Ouest (Cailteux, 1983).

Primary chalcopyrite (-II) and bornite (-II) are the main copper sulphides in the orebodies (e.g. Kambove-Ouest); they grew at the same time as separate or coalescent grains. Carrollite and pyrite-III coexist with copper sulphides-II (mainly chalcopyrite). Chalcopyrite-II includes framboidal pyrite-I, e.g. at Kinsenda (Ngoyi and Dejonghe, 1997). Bornite-II replaces pyrite-I (and -II), e.g. at Kamoto (Bartholomé et al., 1972), as shown by carrollite grains including well-preserved aligned pyrite-I (-II), whereas pyrite grains outside carrollite have been completely replaced by bornite-II (Fig. 11). The textural relations indicate that bornite-II grew after the development of carrollite grains. In the Luiswishi deposit (Loris, 1996; Loris et al., 2002) copper sulphides-II and sulphides of the linnaeite group (linnaeite–siegenite–carrollite/polydymite) formed after those of the pyrite group (pyrite–cattierite–vaesite).

Pyrite, chalcopyrite and bornite grains (sulphides-III) include diagenetic gangue minerals (chlorite, dolomite, quartz) and disseminated copper sulphides-II, indicating late-stage formation of the sulphide grains. Pyrite-III rims copper sulphides-II.

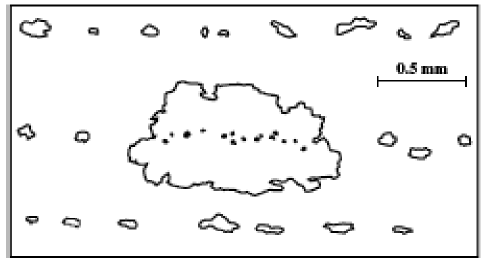

Fig. 11. Grain of carrollite in dolomitic shale of the Upper Orebody (Kamoto-Principal), including a lamina with well-preserved pyrite-I (-II), and showing that this pyrite is replaced by bornite outside carrollite; the sketch also indicates that bornite grew after carrollite (Bartholomé et al., 1972).

Bornite (-II) grains include digenite in bornite-dominant beds (Cailteux, 1986). In these beds, carrollite grains include bornite-II in the centre and digenite-II towards the rim. This indicates that carrollite grew before and after the conversion of bornite into digenite.

Replacement carrollite forms the external rim of chalcopyrite and/or bornite (-II or -III) grains (Fig. 12). The transition between carrollite rims and chalcopyrite or bornite cores is marked by a digenite fringe (Fig. 12a, b), and small pyrite grains occur within the carrollite rims (Fig. 12c). Pyrite (III, IV), chalcopyrite and bornite (-IV) overgrow these parageneses (Fig. 12d). Some carrollite grains include copper sulphides showing replacement textures by carrollite; others show microfractures filled by chalcopyrite or bornite (-IV). In Zambia-type deposits (e.g. Musoshi), bornite frequently includes chalcopyrite both as lattice or irregular exsolutions (Cailteux, 1973, 1974). Similar parageneses occur in the Shituru lower orebody, forming also several generations of sulphides (Lefebvre, 1974).

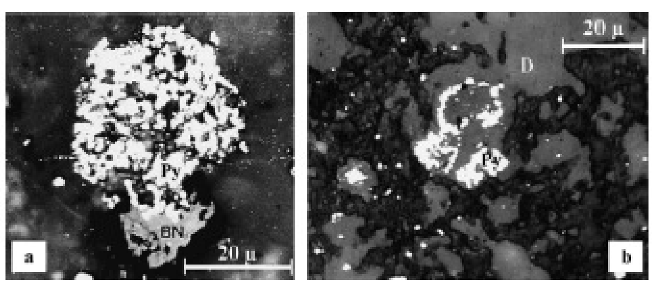

Fig. 10. (a) Framboidal pyrite (Py) associated with later bornite (BN). Bornite includes framboidal pyrite. Upper Orebody (S.D.B.), sample No. 822, D.H. Kwf-1148, Kambove-Ouest deposit (Cailteux, 1983). (b) Framboidal pyrite (Py) included in dolomite (D). Grey R.A.T., sample No. 1874, D.H. Kw-236B, Kambove-Ouest deposit (Cailteux, 1983).

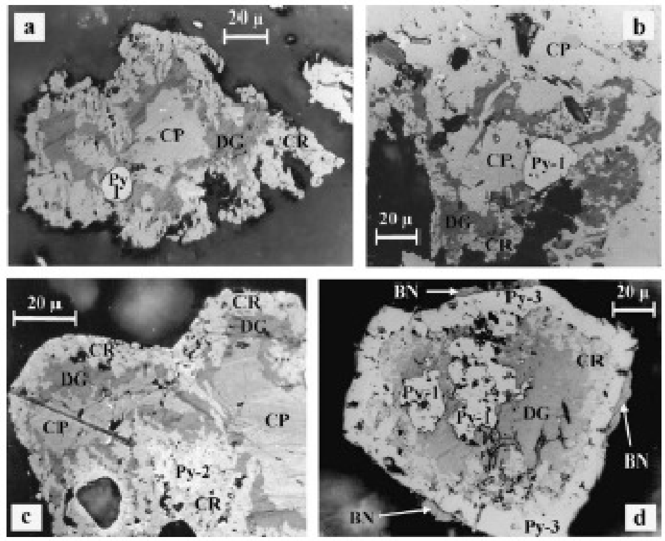

Fig. 12. (a) Incomplete transformation of a chalcopyrite grain into carrollite and digenite; relict chalcopyrite (CP) occurs in the centre of the grain; digenite (DG) occurs between chalcopyrite and carrollite (CR); early pyrite (Py-1) grains are included in copper sulphides; (b) Detail of the same paragenesis; (c) Occurrence of pyrite grains (Py-2) within carrollite. Grey R.A.T., sample No. 1291, D.H. Kwf-1150, Kambove-Ouest deposit (Cailteux, 1983); (d) Late pyrite (Py-3) partly surrounded by late bornite (BN). S.D.B., sample No. 1511, D.H. Kwf-1138, Kambove-Ouest deposit (Cailteux, 1983).

6.2. Relations between sulphides and gangue minerals

Abundant nodules or beds of anhydrite occur in the Zambia-type Ore Shale (e.g. Nkana, Mufulira) and there is evidence for replacement of evaporitic minerals by calcite–dolomite, quartz, bornite and chalcopyrite (Annels, 1974). This author showed that, in the Mufulira deposit, mineralised zones correspond to areas in the orebodies with little or no anhydrite content, whereas high anhydrite contents mark barren or sparsely mineralised zones. Pseudomorphs after anhydrite nodules occur in S.D.B. and at the base of the Kambove Formation within the Congo-type deposits (Bartholomé et al., 1972; Annels, 1974; Katekesha, 1975; Cailteux, 1978a,b). These nodules were completely replaced by dolomite, quartz, pyrite and copper–cobalt sulphides in the orebodies and, within the same stratigraphic units, by dolomite, quartz, pyrite in barren rocks.

The relationship between sulphides and leucoxene-rutile were documented in both Congo-type and Zambia-type deposits. In the Musoshi (Zambia-type) deposit (Cailteux, 1973; Cailteux and Dimanche, 1973), the barren rocks below and above the orebodies are marked by detrital ilmenite (Ilm) showing partial to complete conversion into leucoxene (Lx), with intermediate products (Ilm+Lx or Rt-Lx). These minerals are associated with diagenetic hematite. In the Musoshi orebodies, the conversion of ilmenite into Lx-Rt is complete, and 65% of the leucoxene-rutile grains show associations and intergrowths with pyrite-I, -II and/or copper sulphides-II, whereas 25% of the leucoxene-rutile and 10% of the sulphides occur in isolated grains (Cailteux and Dimanche, 1973). A similar diagenetic mineral association occurs in clastic rocks from the Congo-type orebodies (S.D.S. and S.D.B./upper orebody; Fig. 13), e.g. at Kipapila-Kimpe (Cailteux and Lefebvre, 1975), Etoile (Lefebvre and Cailteux, 1975) and Kambove-Ouest (Cailteux, 1978a, 1983). In the S.D.S., this association coexists with framboidal pyrite-I.

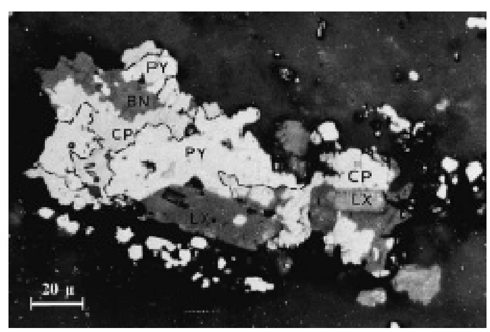

Fig. 13. Relict Leucoxene (Ti–Fe oxide, LX) associated with pyrite (Py), chalcopyrite (CP), bornite (BN) assemblage; note the diagenetic destabilisation of detrital ilmenite releasing iron presumably fixed into copper sulphides. Upper orebody (S.D.B.), sample No. 822, D.H. Kwf-1148, Kambove-Ouest deposit (Cailteux, 1983).

In the Kambove Formation, carrollite is the major sulphide in talc-dolomite bearing beds and layers (Figs. 4 and 5), whereas dolomite–quartz bearing beds host mainly copper sulphides (Cailteux, 1983). Talc in these rocks is diagenetic and presumably results from an early sepiolite that coexisted with calcite (converted into diagenetic dolomite) instead of growing from the reaction between dolomite and quartz (Bartholomé, 1966; Cailteux, 1979). However, a metamorphic origin for this talc remains possible.

6.3. Relations between orebodies and deformation events

In Congo, the orebodies were tectonically dismembered, forming part of thrust sheets (e.g. Derriks and Vaes, 1956; Derriks and Oosterbosch, 1958; Mendelsohn, 1961b; Demesmaeker et al., 1963), related to the first Lufilian compressional deformation event known as the Kolwezian tectonic event (Kampunzu and Cailteux, 1999 and references therein). The heterogenous distribution of strain during this event with the maximum strain focused along thrust sense shear zones, possibly controlled by evaporitic layers (Cailteux, 1994; Cailteux and Kampunzu, 1995), explains the absence of strong fabric within the rocks and thus the good preservation of sedimentary/diagenetic textures. In Zambia, a stronger fabric occurs in some deposits and is registered in both sulphides and gangue minerals (e.g. Nkana, Luanshya, Mufulira; Mendelsohn, 1961b; Brandt et al., 1961).

Metamorphism and/or hydrothermal alteration (fluids escape during compressional tectonics) generated variable re-equilibration, remobilization and secretion of sulphides into late- to post-kinematic veins both in Zambia and Congo (e.g. Garlick, 1961b, 1964; Mendelsohn, 1961c; Cailteux, 1983, 1997; Sweeney, 1987; Cailteux and Kampunzu, 1995; Loris, 1996). In the orebodies, minor remobilisation of stratiform ores is shown by a few cross-cutting mineralised veins surrounded by centimetre-wide zones within which stratiform sulphides have been depleted. A few centimetres away from these veins, the fine primary compositional zoning of the disseminated stratiform sulphides is well preserved. In the Musoshi deposit, the copper content in the "depleted" orebody rocks affected by fractures related to the Lufilian orogeny is ~0.03 wt.% Cu, whereas the adjacent undepleted orebody contains more than 3.0 wt.% Cu (Lefebvre and Tshiauka, 1986; Richards et al., 1988).

7. Isotopic geochemistry

The $\delta^{18}O$ and $\delta^{13}C$ values for Footwall and Ore Shale dolomites in Zambia define two fields in Fig. 14 (Sweeney et al., 1986). $\delta^{18}O$ values for Footwall dolomites are between +20.82 and +26.38‰ SMOW. The Konkola Ore Shale carbonate pseudomorph after anhydrite nodules or lenticles yielded $\delta^{18}O$ values between +14.56 and +16.16‰ SMOW. For comparison, $\delta^{18}O$ present-day mine waters from the Copperbelt yielded values of −6.2‰ SMOW (Sweeney et al., 1986).

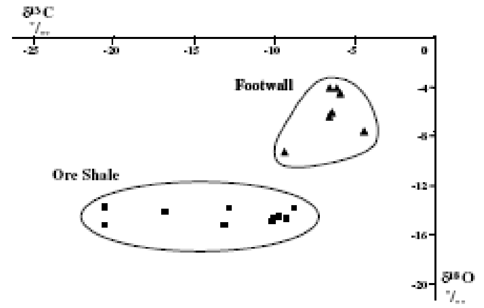

Fig. 14. Values of $\delta^{18}O$ plotted against $\delta^{13}C$ for carbonates from Zambian Footwall and Ore Shale rocks (Sweeney et al., 1986).

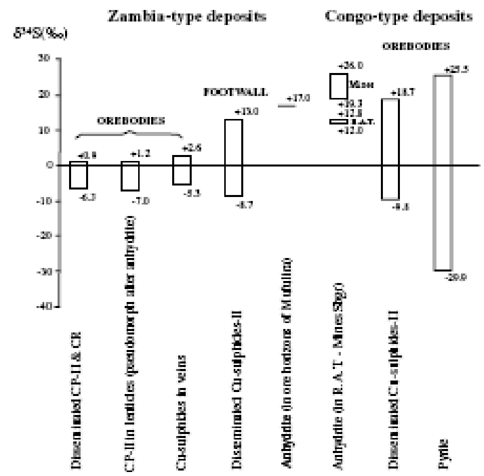

Fig. 15. Sulphur isotope values for sulphides and sulphates from Congo-type deposits (Kamoto, Kambove-Ouest, Luiswishi, Etoile, Ruashi; data from Okitaudji, 1989 and Lerouge et al., 2004), sulphides from the Zambian Ore Shale, Footwall and veins at Konkola, and sulphates from Mufulira ore horizons (data from Sweeney et al., 1986). CP = chalcopyrite; CR = carrollite.

Sulphur isotopic data on sulphides from Cu–Co mineralization in Congo and Zambia are dispersed (Fig. 15). However they show a consistent large range of $\delta^{34}S$ values (Jensen and Dechow, 1962; Dechow and Jensen, 1965; Sweeney et al., 1986; Okitaudji, 1989; Hoy and Ohmoto, 1989; McGowan et al., 2003; Lerouge et al., 2004), from high negative to high positive values, which characterize the sediment-hosted deposits (e.g. Ohmoto and Rye, 1979; Krouse, 1980; Misi et al., 2000; McGowan et al., 2003 and others). The range of $\delta^{34}S$ values (Fig. 15) are in agreement with values of sulphides resulting from a bacterial reduction of marine sulphates at superficial temperatures (<50 °C). However, for deposition in Congo, Hoy and Ohmoto (1989) suggested that the high positive $\delta^{34}S$ values originated from an input of hydrothermal sulphur characterized by a $\delta^{34}S \sim +9‰$. The same hypothesis is also proposed for the Meso- and Neoproterozoic lead–zinc deposits of the São Francisco Craton (Misi et al., 2000). Rare $\delta^{34}S$ sulphate analyses from host rocks are $\sim +17‰$ at Mufulira in Zambia (Sweeney et al., 1986) and $+22.6‰$ in the Mines Subgroup (average) at Kolwezi (Okitaudji, 1989). These values are quite close to the reference value of Neoproterozoic seawater (Claypool et al., 1980), and tend to confirm a largely marine origin for the sulphur.

A detailed investigation of the relations between $\delta^{34}S$ of individual sulphides and the lithostratigraphic position at Konkola in Zambia (Fig. 16a; Sweeney et al., 1986) and Luiswishi in Congo (Fig. 16b; Lerouge et al., 2004) indicates a strong stratigraphic control of $\delta^{34}S$ in sulphides. These relations suggest an introduction of sulphur to the sediments during sedimentation and early diagenesis. According to Ohmoto and Rye (1979), variations of $\delta^{34}S$ values may be interpreted in terms of transgression–regression events, i.e. $\delta^{34}S$ values become lighter (high negative values down to $-70‰$) during transgressive events, whereas they become heavier (high positive values up to $+70‰$) during regressive events. Consequently, both in Congo and Zambia, the high $\delta^{34}S$ sulphide values from the base of the orebodies were probably produced by $\delta^{34}S$-depletion in a main reservoir during a regressive period, marking a basin closed from the seawater. The decrease of $\delta^{34}S$ values, down to $\sim -15‰$ in the Ore Shale in Zambia, suggests that the system was progressively open to a SO_4-rich source, marking a transgressive event during the deposition of the lower part of the Ore Shale (Units A and B), followed by a regressive regime during the deposition of its upper part (Units C–E). In Congo the transgressive

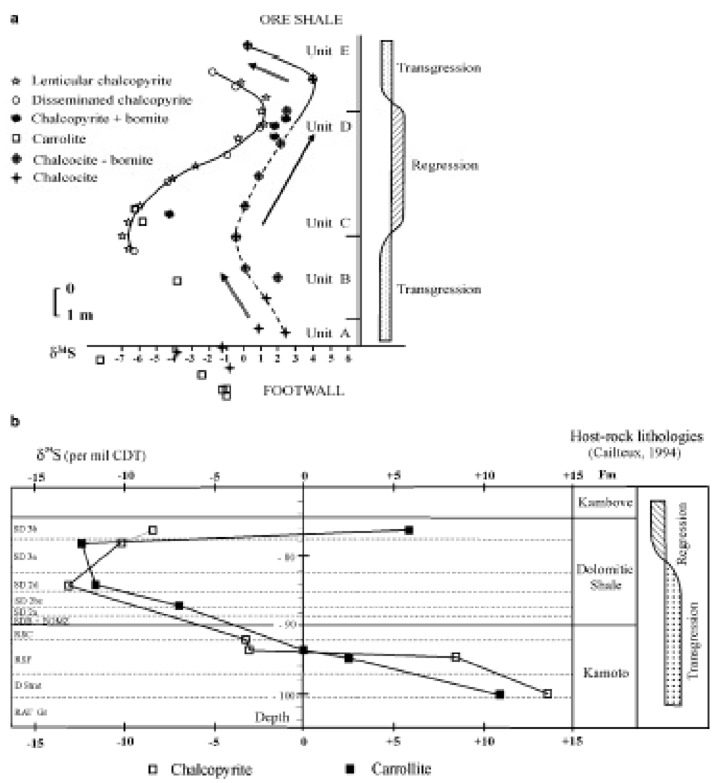

Fig. 16. Sulphur isotope composition of sulphides along vertical sections through (a) the Zambian Ore Shale (Sweeney and Binda, 1989a,b), (b) the Congo-type orebodies in the Luiswishi deposit (Lerouge et al., 2004); the $\delta^{34}S$ sulphide values show the same transgressive–regressive events as those indicated by the host-rock lithologies (Sweeney and Binda, 1989a,b; Cailteux, 1994).

regime was persistent during the deposition of the sediments hosting the Lower and Upper orebodies (Kamoto and Dolomitic Shales Formations). These results are in agreement with the inferred lithological transgressive–regressive evolution of the ore-hosting sediments from the Mines Subgroup in Congo (Bartholomé et al., 1972; Cailteux, 1983, 1994) and the Ore Shale Formation in Zambia (Sweeney et al., 1986).

The sulphur isotopic data of coexisting sulphide pairs at Konkola (Sweeney et al., 1986) and Luiswishi (Lerouge et al. 2004) show heterogeneous isotopic fractionations between the sulphides, indicating crystallization at disequilibrium. In the Luiswishi deposit, chalcopyrite–carrollite isotopic fractionations are systematically reversed when organic matter is abundant. This, along with the large range of $\delta^{34}S$ values, confirms that sulphide $\delta^{34}S$ values are controlled by the sedimentary environment, but also by the presence of organic matter, and probably by complex kinetic processes.

The range of $\delta^{34}S$ values of sulphides in veins is very close to $\delta^{34}S$ values of early associated stratiform sulphides (chalcopyrite, carollite, bornite) indicating a good preservation of the primary sulphur isotopic composition. This strongly suggests a local scale reworking of the early stratiform sulphides, i.e. local recrystallization and neocrystallization of sulphides in veins during the Lufilian tectono-metamorphic events. The preservation of disequilibrium between coexisting sulphides in veins suggests that the reworking was not strong enough to re-equilibrate the $^{34}S/^{34}S$ ratios.

8. Thermometry

François (1973, 1974) indicated that the total thickness of Katangan sedimentary rocks above the stratiform orebodies was ~6 km. Assuming a geothermal gradient of 10 °C/km which is a minimum value deduced from P, T estimates in high-pressure metamorphic rocks in the Katangan/Zambezi belt (Massone et al., 1994; John et al., 2003) and 50 °C/km which is a maximum value calculated by Cluzel (1986) in rocks from Luishia, the temperature at the 6-km burial depth should be between ~60 and 300 °C. The regional metamorphism related to the Lufilian orogeny increases from the north to the south, evolving from zeolite and greenschist facies in Congo to the north up to amphibolite facies in Zambia to the south (e.g. Mendelsohn, 1961b; Oosterbosch, 1962; Drysdall et al., 1972; François and Cailteux, 1981; Tembo, 1994). Most of the Zambian-type deposits in Zambia (e.g. Nchanga, Chambishi, Muliashi, Mufulira, Nkana, Luanshya) and some deposits in Congo (e.g. Musoshi, Kinsenda) evolved under the greenschist facies, possibly around ~350–400 °C (Richards et al., 1988). Particularly at Musoshi, late quartz + biotite + microcline + carbonates + sulphides ± anhydrite ± barite related to the Lufilian orogeny recorded temperatures around 400 °C (fluid inclusion data in quartz, Richards et al., 1988). In northwestern Zambia (Domes area), peak metamorphic conditions at F1 (D1 Kolwezian phase of Kampunzu and Cailteux, 1999) are around 650 °C and 13 kbars, followed by a decompression at 6 kbars (Cosi et al., 1992; Steven and Armstrong, 2003).

9. Fluid inclusions

Fluid inclusions found in gangue minerals (dolomite, magnesite and quartz) from Congo-type Kamoto-Principal, Shinkolobwe, Kambove-Ouest and Luiswishi orebodies (Pirmolin, 1970; Ngongo, 1975b) are of two types: (1) two phase- (liquid–gas) inclusions of small size in dolomite or quartz, CO_2-free, with yield temperatures around 70 °C and salinities in the range 7–10 wt.%; (2) three phase-(solid–liquid–gas) inclusions in dolomite grains from R.S.C., hosting one to three different types of solid phases (NaCl, KCl and $CaSO_4$) and containing CO_2, with yield tem- peratures of ⩾200 °C and salinities estimated around 40 wt.%.

Audeoud (1982) and Audeoud et al. (1984), working on fluid inclusions contained in dolomitic veinlets of the R.A.T. formations and on identical inclusions associated with the anchimetamorphic recrystallization, showed that the aqueous phase is the most important one, and confirmed the very high salinity of this phase, i.e. containing more than 60 wt.% of dissolved salts ($MgCl_2$, $CaCl_2$). The NaCl and KCl concentrations in these inclusions are relatively low, which is consistent with the R.A.T. composition (Kampunzu et al., this volume).

In Zambia, Sweeney (1987) found that: (1) fluid inclusions in quartz veins cross-cutting the Ore Shale at Konkola show post-trapping alteration features; (2) inclusions of the same vein system are characterized by varying fluid chemistry; (3) hydrocarbon liquid inclusions are present in several samples. (4) fluid chemistry variation corresponds to diagenetic changes in the different lithologies during the basin evolution. The author concluded that the veins represent a post-formational tectono-thermal event, and formed by lateral secretion of fluids during late diagenetic dewatering at temperatures of ~120 °C.

Fluid inclusions in quartz from quartz-hematite veins cutting the Footwall at Musoshi (Richards et al., 1988) contain halite-saturated fluid, with a minimum salinity of 28–39 wt.% NaCl and 15–17 wt.% KCl, minor amounts of CO_2, and also contain Fe, Ca, Mn. They yielded temperatures of 275–397 °C. These authors concluded that the hydrothermal event post-dates the stratiform copper deposition and may have been linked to compressional deformation and metamorphism during the Lufilian orogeny.

Fluid inclusions from early quartz associated with pyrite and carrollite (pseudomorph after anhydrite) in the Chambishi orebody, yielded salinities in the range of 9–16 wt.%, whereas fluid inclusions from syn-kinematic veins yielded higher salinities between 16 and 22 wt.% (Annels, 1989).

Recent studies by Greyling et al. (2002) on various tectonic settings (pre-deformational, syn-tectonic, post-deformational) showed the following scenario. (1) There are primary and secondary inclusions of H_2O–NaCl–$CO_2 \pm CH_4$ compositions with a salinity of 23 wt.% NaCl equivalent in mineralised and non-mineralised quartz veins, formed prior to deformation and folding from deposits in Zambia (e.g. Chambishi). (2) Representative of syn-tectonic fluids, primary inclusions in quartz veins in the Nchanga open pit contain NaCl-saturated fluids with varying liquid–vapour–solid ratios suggesting heterogeneous trapping. (3) Primary and secondary inclusions from mineralised K-feldspar–quartz–biotite-anhydrite assemblage veins cross-cutting the orebodies in the Nkana synclinorium, and representative of post-tectonic fluids, contain H_2O–NaCl solutions which reflect two end-members fluids: (A) low salinity (8–14 wt.% NaCl equiv.) and high Th (300–400 °C); (B) high salinity (14–23 wt.% NaCl equiv.) and low Th (100–150 °C). The authors concluded that (1) low temperature—high salinity fluids may be characteristic of basinal—early diagenetic brines, whereas high-temperature—low salinity fluids are possibly derived from later regional metamorphic events.

10. Discussion

There are no data to support the genetic ore model involving a widespread circulation of hydrothermal fluids ascending along rift fractures and deriving metals from deep-seated mafic rocks, as proposed by Annels (1974, 1979, 1989), Annels and Simmonds (1984) and Lefebvre (1989). Indeed, fracture-filling ores expected to mark mineralising fluid flow paths are unknown and there is no link between Cu–Co distribution and Upper Roan/Dipeta igneous mafic rocks (Sweeney et al., 1991a,b; Kampunzu et al., 2000, this volume) in Congo and Zambia. No large plutonic body able to supply the amount of metals known in the Copperbelt has ever been detected by gravity and aeromagnetic surveys beneath the mineralised section of the Katangan belt (Sweeney et al., 1991a,b; Sebagenzi, 1993, 1997a,b; Gecamines, unpublished aeromagnetic data).

Similarly, there are no data to support the hypothesis of Unrug (1988, 1989), assuming the existence of two pulses of hydrothermal ore-forming fluids that supplied metal to the Roan Subgroup "aquifers". This author suggests a two-stage model including: (1) Co–Ni-PGM hydrothermal fluids linked to the emplacement of mafic magmas in the Copperbelt during the deposition of Nguba Group sediments; (2) convective circulation of basinal ore solutions driven by a thermal gradient and with leaching of metals from Nguba pelites, incorrectly inferred by the author to contain ~50% of igneous mafic material. Several authors (e.g. Sweeney and Binda, 1989a,b) stressed already that this model is untenable. The bulk of the ore sulphides were deposited at the same time as the deposition of the Mines Subgroup and thus predate the deposition of the Nguba Group. The lack of spatial relations between Cu–Co mineralisation and igneous mafic rocks has already been stressed above. The sulphide zoning reported above cannot be explained by this model.

Several authors (e.g. Brown and Chartrand, 1986; Haynes, 1986; Rose, 1989; Walker, 1989) suggested that dewatering of "red beds" located stratigraphically beneath the sediment-hosted ore deposits could be the main source of copper-(cobalt) mineralizing fluids in the Copperbelt stratiform orebodies. However, available data do not support this attractive model. For example, geochemical data (Kampunzu et al., this volume) show that: (1) the transition metals content in the footwall sedimentary rocks is higher than average content in normal clastic rocks and there is no geochemical evidence to support loss of these metals in the footwall; (2) there is no evidence of widespread diagenetic copper-bearing dewatering-veins in the footwall rocks; (3) accumulation of at least 1850 million tons of copper contained in the Copperbelt requires the erosion and the deposition in the Katangan basin of 10^{14} m^3 of source rocks, which is about 100 times the volume of footwall sedimentary rocks in the Lufilian Arc. On the other hand, occurrences of copper are known in the basement: (1) the Samba deposit granitoids (50 million tons at 0.7 wt.% Cu); (2) the Muva phyllites south of the Nkana basin (3.6-m wide zone at 3.6 wt.% Cu); (3) the Nchanga Red Granite (1.5 million tons at 1.5 wt.% Cu); >5000 ppm Cu over a large area below the Chingola-Nchanga orebodies; several pockets reported from a number of mines and prospects in the Copperbelt (Binda, 1997 and references therein; Hitzman, 2000).

The Copperbelt primary mineralisation displays very fine sulphide layering and the ore and host rock grain sizes are strongly positively correlated. The ore sulphides occur along foresets of cross-bedding and bedding planes and they are affected by pre-consolidation sedimentary structures such as sedimentary truncation and slumping (Garlick, 1961b, 1989). The orebodies are affected by the oldest Lufilian compressional structures such as thrusts related to the Kolwezian tectonic event (Kampunzu and Cailteux, 1999). Therefore, these orebodies cannot be linked to fluids from syn-orogenic metamorphic dewatering even if they display features indicating partial reworking of primary ores during Lufilian tectonic-metamorphic events. The most important among these features are the following: (1) one set of low-salinity fluid inclusions yield equilibration temperatures $\geqslant 200$ °C, contrasting with lower temperatures (<100 °C) obtained on high-salinity inclusions preserving primary features (Pirmolin, 1970; Audeoud, 1982; Audeoud et al., 1984; Sweeney, 1987; Richards et al., 1988; Annels, 1989; Greyling et al., 2002); (2) local syn-kinematic hydrothermal leaching (Ngongo, 1975a; Lefebvre, 1976b; Cailteux and Kampunzu, 1995; Cailteux, 1997) indicates small scale metamorphic remobilisation of hypersaline fluids (cf. fluid inclusion composition) inducing recrystallisation of both gangue and ore minerals and local development of barren and mineralised veins; (3) kyanite–serpentine–florencite and paragonite–phengite assemblages in veins indicate temperatures up to 400 °C in the presence of hypersaline fluids (Lefebvre and Patterson, 1982; Cluzel, 1986). The genetic model developed below puts emphasis on the mineralising processes that were the most important in the formation of the primary orebodies.

The Mines/Musoshi orebodies are lithologically/stratigraphically bound to more or less evaporitic tidal flat/subtidal shales-carbonates in Congo and to their lateral correlatives in Zambia. All rocks hosting Cu–Co sulphide in Congo-type orebodies (Grey R.A.T.–D.Strat.–R.S.F.–S.D.B.–Kambove Formation) were deposited under reducing conditions, in a tidal flat/subtidal environment, during a major transgressive–regressive event. They overlie continental siliciclastic sedimentary rocks (Red R.A.T. in Congo-type and Mutonda in Zambia-type orebodies) deposited under an oxidized, hot, arid to semi-arid environment. Variegated R.A.T. represents the transition zone between the oxidized footwall sedimentary rocks and the main orebodies. This transitional lithology indicates the existence of a reducing/oxidizing front (Cailteux, 1978a, 1994). A thinner but similar transition zone occurs over tens of centimetres between the Zambian Ore Shale and its Footwall (e.g. Musoshi; Cailteux, 1973).

The earliest sulphides (pyrite-I, Co–Ni-pyrite-II, chalcopyrite-I, bornite-I) were deposited before the lithification of the host rocks, i.e. they are syngenetic to early diagenetic. This interpretation is based on the supposition that early diagenetic processes start when sedimentation is ongoing. Framboidal pyrite-I is a syngenetic mineral since such texture marks direct precipitation of FeS_2 from solutions (Berner, 1964, 1970) or bacterial reduction of seawater sulphates (Annels, 1974; Sweeney et al., 1987). Inclusions of copper sulphides-I in framboidal pyrite indicate that the earliest Cu-sulphides precipitated early, before some framboidal pyrite and thus represent also syngenetic minerals. The increase of Cu–Co–Ni content from the centre (pyrite-I) to the margin (pyrite-II) of grains reflects an increase of transition metal concentration in the interstitial water, possibly indicating the first steps of evaporation in the sedimentary basin, yielding metal-rich brines. High transition metal content in host rock primary minerals such as dolomite (Sweeney and Binda, 1989a,b; Loris, 1996) indicates that the transition elements were readily available and even concentrated in the depocentre water during sediment deposition.

Pyrite group sulphides (pyrite, cattierite, vaesite) were deposited before Cu–Co sulphides-II. According to Craig and Vaughan (1979), the pyrite group forms a crystallisation sequence pyrite → Co-pyrite → cattierite + thiospinel or vaesite (e.g. at Luiswishi), marking Fe–Co–Ni compositional changes of the ore-forming fluids.

The second generation of sulphides (Cu–Co sulphides-II) replaces or includes sulphides of the first generation (i.e. bornite replacing pyrite, chalcopyrite including framboidal pyrite). Intergrowth of Cu–Co sulphides-II with diagenetic minerals (e.g. chlorite, leucoxene-rutile) indicates that they grew during diagenesis. Diagenetic conversion of detrital ilmenite into leucoxene and rutile released at least part of the iron required for sulphides-II growth in reducing conditions that prevailed in rocks hosting most orebodies.

Replacement textures within the external rim of copper sulphides-II are also related to diagenetic reactions. An increase of cobalt concentration in the brine and its reaction with copper sulphide grains led to the growth of carrollite at their rims. The reactions involved are as follows (Cailteux, 1983, 1986):

$$2\,\underset{\text{chalcopyrite}}{CuFeS_2} + 2Co^{2+} \rightarrow \underset{\text{carrollite}}{CuSCo_2S_3} + Cu^{2+}\uparrow + 2Fe^{2+}\uparrow$$

$$3\,\underset{\text{bornite}}{Cu_5FeS_4} + 6Co^{2+} \rightarrow 3\,\underset{\text{carrollite}}{CuSCo_2S_3} + 12Cu^{2+}\uparrow + 3Fe^{2+}\uparrow$$

The copper released during these reactions enhanced, at the contact with carrollite, the conversion of chalcopyrite and bornite into digenite. Small pyrite crystals within the carrollite fringe could be linked to the iron released during the above reactions. Excess iron was probably released to the interstitial fluid. Positive cobalt anomalies in the hangingwall of the Congo-type orebodies indicate that the brines were still enriched in cobalt after the deposition of Co-sulphides in the orebodies.

Sulphur isotopic data on nodular and lenticular anhydrite from the orebodies and barren rocks from the same unit indicate that anhydrites formed by evaporation of seawater under supratidal or sabkha conditions, requiring a major sulphate super-saturation of the mineralising brines. The sulphide isotopic data show that the source of sulphur was seawater sulphate ions. They also support growth of sulphides at low temperature (less than 100 °C) by bacterial reduction of sulphate ions in the brines and possibly by reaction with earlier anhydrite (Annels, 1974; Sweeney and Binda, 1989a,b). This process liberated the sulphur necessary for sulphide growth. Isotopic data also identify the occurrence of two generations of sulphides (Hoy and Ohmoto, 1989): the first (50–75 vol.% sulphides) is syngenetic to early diagenetic whereas the second (25–50 vol.% sulphides) is attributed to super-saturated copper-bearing fluids generated at the depositional site during synkinematic metamorphic processes (Cailteux and Kampunzu, 1995; Kampunzu and Cailteux, 1999). Fluid inclusion data reviewed above (e.g. Greyling et al., 2002) coupled with field and petrologic observations show that: (1) the first group of sulphides grew probably at less than 100 °C, and this is compatible with sulphide crystallisation at low temperature by bacterial reduction of sulphate ions in brines (Annels, 1974; Sweeney and Binda, 1989a,b); (2) the second group of sulphides grew during the Lufilian orogenesis from metamorphic fluids reworking the syngenetic to diagenetic mineralization (Cailteux and Kampunzu, 1995; Cailteux, 1997; Kampunzu and Cailteux, 1999).

Brine oversaturation in metals resulting in the deposition of the syngenetic to early diagenetic sulphides was controlled by evaporation, probably within sabkha basins (Cailteux, 1986; Garlick, 1989). Changes in Eh–pH conditions may explain the consistent sulphide zonation in the Copperbelt orebodies (Cailteux, 1986).

The model of primary concentration of copper in the Copperbelt stratiform orebodies involves the mixing of oxidized mineralising brines from the hypersaline lagoon with interstitial reducing water rich in organic compounds. This model is supported by: (1) the occurrence of relict evaporitic beds at the top of the R.A.T. Subgroup and by the collapse dissolution breccias in the Kambove Formation in Congo. This implies at least two periods of prograding sabkha-type lagoons, the first generating the lower and upper orebodies and the second forming the third, minor orebody; (2) the strong lithostratigraphic control on the position of the orebodies in Zambia and in Congo (more than 700 km along strike) and the close link between the mineralisation and anoxic shallow-water intertidal to supratidal host-sedimentary rocks. These data and the stable isotopic compositions discussed above indicate that sedimentary processes played a key-role in the metallogenetic processes.

Orebodies or sub-economic Cu sulphide ores are hosted in footwall sedimentary rocks deposited under oxidized conditions in the Zambia-type siliciclastic Mutonda Formation (e.g. Muliashi-South in the Luanshya district, Chingola; Binda, 1997). They are lenticular bodies located at different stratigraphic levels within the Mutonda unit (Fig. 6). Van Eden and Binda (1972) and Binda (1987) suggest a downward migration of mineralising diagenetic brines remobilising copper from the Ore Shale to the porous footwall formation. However, the occurrence in these peculiar orebodies of pyrite-I included in copper sulphides-II at Kinsenda (Ngoyi and Dejonghe, 1997) suggests an early diagenetic biogenic reduction of seawater sulphates in the precursor sediments. This could indicate that local redox fronts existed in these sediments, and that the same mineralising process as in the Ore Shale acted in the Mutonda Formation.

The model proposed in this paper links the influx of metals to the Katangan sedimentary basin to the erosion of pre-Neoproterozoic basement terrains (transportation in solution). Geochemical and geological data indicate that the Archaean Zimbabwe craton and the Palaeoproterozoic basement complex in the Bangweulu Block and within the Copperbelt represent the main sources of sediments and metals accumulated in the Katangan basin. The basement terrains particularly host lithological units with potential for the supply of large amounts of copper and cobalt and containing the required additional metal association Ni, Au, Ag, PGE (e.g. several Cu occurrences in the basement complex, cobalt in Ni-laterites formed on Archaean low-grade Ni–Co–Au–PGM deposits in the Zimbabwe craton). Some metals (e.g. U, Sn, Ta, W) most probably originated from the erosion of post-orogenic Kibaran tin-granites (Caron et al., 1986) and this is supported by the presence of detrital cassiterite, wolframite, tantalite in the orebodies in the Kolwezi mining district (Jedwab, 1997) and late Mesoproterozoic zircons in the Mwashya tuffs (Rainaud et al., 1999, 2003).

In the case of the Lower Mwashya orebodies at Shituru, the Cu–(Co) mineralization is hosted in dolomite displaying lithological similarities with those hosting the Lower orebody in the Mines Subgroup. Minor ore in the pyroclastic rocks at Shituru probably originated from remobilisation of local sediment-hosted mineralization.

11. Conclusions

The central African Copperbelt represents a Neoproterozoic stratiform sediment-hosted province >700 km long and <100–150 km wide. It contains >140 Mt copper and >6 Mt cobalt (mined out production, ore reserves and resources). Although the Congo-type and Zambia-type orebodies show some differences (e.g. clastic vs. carbonate host rocks), they display a large number of analogies, including: (1) their location in laterally correlative lithostratigraphic units deposited in supratidal to sabkha-type highly saline environments; (2) similarities of ore textural features with predominantly disseminated sulphides closely linked to structures such as sedimentary lamination, cross-bedding, etc.; (3) identical sulphide parageneses; (4) identical zoning of sulphides related to primary variation of Eh–pH parameters during ore deposition; (5) relatively low (<100 °C) crystallisation temperature of primary syngenetic/early diagenetic sulphides versus higher (⩾200 °C) crystallisation temperature for late diagenetic/metamorphosed sulphides. The low crystallisation temperatures for the primary sulphides are similar to temperatures recorded during bacterial mediated sulphate reduction, producing sulphur required for growth of sulphides under reducing conditions, e.g. by bacterial reduction of seawater sulphate ions.

The following are therefore critical parameters for the development of world class sediment-hosted stratiform deposits in the central African Copperbelt: (1) availability of large tonnage of metals in the hinterland (Palaeoproterozoic and Archaean basement), subjected to erosion during the early Neoproterozoic; (2) arid climate in the depositional area where the evaporation induced a natural pre-concentration of metals; (3) development of reducing conditions during the deposition of the Mines Subgroup (Congo-type) and its correlative the Musoshi Subgroup (Zambia-type) rock association. This reducing environment triggered the crystallisation of syngenetic and early diagenetic sulphides, and therefore the copper–cobalt deposits in the central African Copperbelt are typical syngenetic-early diagenetic deposits; (4) late diagenetic, metamorphic and relatively recent oxidation processes reworked the orebodies enhancing metal grades in some deposits.

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References

Annels, A.E., 1974. Some aspects of the stratiform ore deposits of the Zambian Copperbelt and their genetic significance. In: Bartholomé, P. (Ed.), Gisements stratiformes et provinces cuprifères. Centenaire Société Géologique de Belgique, Liège, pp. 235–254.

Annels, A.E., 1979. The genetic relevance of recent studies at Mufulira Mine, Zambia. Annales Société Géologique de Belgique 102, 431–449.

Annels, A.E., 1989. Ore genesis in the Zambian Copperbelt with particular reference to the northern sector of the Chambishi basin. In: Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C., Kirkham, R.V. (Eds.), Sediment-Hosted Stratiform Copper Deposits. Geological Association of Canada, Special Paper, vol. 36, pp. 427–452.

Annels, A.E., Simmonds, J.R., 1984. Cobalt in the Zambian Copperbelt. Precambrian Research 25, 75–98.

Annels, A.E., Vaughan, D.J., Craig, R.J., 1983. Conditions of ore minerals formation in certain Zambian deposits with special reference to the role of the cobalt. Mineralium Deposita 18, 71–88.

Armstrong, R.A., Robb, L.J., Master, S., Kruger, F.J., Mumba, P.A.C.C., 1999. New U–Pb age constraints on the Katangan sequence, central African Copperbelt. Journal of African Earth Sciences 28, 6–7.

Audeoud, D., 1982. Les minéralisations uranifères et leur environnement à Kamoto, Kambove et Shinkolobwe (Shaba, Zaïre). Pétrographie, géochimie et inclusions fluides. Thèse de 3ème cycle, Lyon (France), 211 p.

Audeoud, D., Moine, B., Poty, B., 1984. Minéralisations uranifères et milieux confinés au Shaba. Gréco 52, Société de Géologie Appliquée, Paris.

Bartholomé, P., 1962. Les minerais cupro-cobaltifères de Kamoto (Katanga-Ouest), I. Pétrographie—II. Paragenèses. Studia Universitatis "Lovanium", Faculté des Sciences, University of Kinshasa, vol. 14, 40 p. and vol. 16, 24 p.

Bartholomé, P., 1963. Sur la zonalité dans les gisements du Copperbelt de l'Afrique Centrale. In: Symposium on Problems of Postmagmatic Ore Deposition, Prague, vol. 1, pp. 317–321.

Bartholomé, P., 1966. Sur l'abondance de la dolomite et de la sépiolite dans les séries sédimentaires. Chemical Geology 1, 33–48.

Bartholomé, P., 1969. Kamoto (Katanga) et White Pine (Michigan): deux gisements stratiformes de cuivre. Académie Royale des Sciences d'Outre-Mer, Bulletin des Séances, pp. 397–410.

Bartholomé, P., 1974. On the diagenetic formation of ores in sedimentary beds, with special reference to Kamoto, Shaba, Zaïre. In: Bartholomé, P. (Ed.), Gisements stratiformes et provinces cuprifères. Centenaire de la Société Géologique de Belgique, Liège, pp. 203–213.

Bartholomé, P., Evrard, P., Katekesha, F., Lopez-Ruiz, J., Ngongo, M., 1972. Diagenetic ore-forming processes at Kamoto, Katanga, Republic of the Congo. In: Amstutz, G.C., Bernard, A.J. (Eds.), Ores in Sediments. Springer-Verlag, Heidelberg, pp. 21–41.

Bartholomé, P., Katekesha, F., Lopez-Ruiz, J., 1971. Cobalt zoning in microscopic pyrite from Kamoto, Republic of the Congo. Mineralium Deposita 6, 167–176.

Berner, R.A., 1964. Iron sulfides formed from aqueous solution at low temperatures and atmospheric pressure. Journal Geology 72, 293–306.

Berner, R.A., 1970. Sedimentary pyrite formation. American Journal of Science 268, 1–23.

Binda, P.L., 1972. Zircons of the Nchanga Granite and overlying metasediments, Zambia. In: 24th International Geological Congress, Section 1, pp. 179–186.

Binda, P.L., 1987. Depositional environment and copper mineralization of the footwall rocks at Muliashi South, Zambian Copperbelt. In: Matheis, G., Schandelmeier, H. (Eds.), Current Research in African Earth Science. Balkema, Rotterdam, pp. 397–400.

Binda, P.L., 1994. Stratigraphy of Zambian orebodies. In: Kampunzu, A.B., Lubala, R.T. (Eds.), Neoproterozoic Belts of Zambia, Zaire and Namibia. Journal of African Earth Sciences 19, 251–264.

Binda, P.L., 1997. Cenozoic analogies for the Katangan copper deposits of Zambia. In: Charlet, J.-M. (Ed.), Colloque International Cornet, Gisements stratiformes de cuivre et minéralisations associées, Mons (1994). Académie Royale des Sciences d'Outre-Mer, pp. 199–215.

Binda, P.L., Mulgrew, J.R., 1974. Stratigraphy of copper occurences in the Zambian Copperbelt. In: Bartholomé, P. (Ed.), Gisements stratiformes et provinces cuprifères. Centenaire de la Société Géologique de Belgique, Liège, pp. 215–233.

Binda, P.L., Van Eden, J.G., 1972. Sedimentological evidence on the origin of the Precambrian Great Conglomerate, (Kundelungu tillite) Zambia. Palaeogeography, Palaeoclimatology, Palaeoecology 11, 151–168.

Brandt, R.T., Burton, C.C.J., Maree, S.C., Woakes, M.E., 1961. Mufulira. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 411–464.

Brock, B.B., 1961. The structural setting of the Copperbelt. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 81–89.

Brown, A.C., Chartrand, F.M., 1986. Diagenetic features at White Pine (Michigan), Redstone (N.W. Territories, Canada) and Kamoto (Zaïre). In: Friedrich, G.H., Genkin, A.D., Naldrett, A.J., Ridge, J.D., Sillitoe, R.H., Vokes, F.M. (Eds.), Geology and Metallogeny of Copper Deposits, Part IV, Sediment-Hosted Deposits. 27th International Geological Congress, Moscow (1984), Special Publication 4, Society for Geology Applied to Mineral Deposits. Springer-Verlag, Heidelberg, pp. 390–397.

Buffard, R., 1988. Un rift intracontinental du Précambrien Supérieur: le Shaba méridional (Zaïre). Evolution sédimentaire et tectonique du Supergroupe de Roan au Groupe du Kundelungu inférieur (Supergroupe du Kundelungu). Thèse de Doctorat en Sciences, University of Maine, France, 316 p.

Byamungu, B.R., Giordano, R., Kampunzu, A.B., Male, C.N., 1979. A propos du Kibarien (Précambrien Moyen) de la région du barrage de N'Zilo (Shaba, Zaïre). Annales de la Faculté des Sciences, Lubumbashi 2, 39–48.

Cahen, L., 1954. Géologie du Congo Belge. Vaillant Carmanne, Liège, 577 p.

Cailteux, J., 1973. Minerais cuprifères et roches encaissantes à Musoshi, Prov. Shaba (Rép Zaïre). Annales de la Société Géologique de Belgique 96, 495–521.

Cailteux, J., 1974. Les sulfures du gisement cuprifère stratiforme de Musoshi, Shaba, Zaïre. In: Bartholomé, P. (Ed.), Gisements stratiformes et provinces cuprifères. Centenaire de la Société Géologique de Belgique, Liège, pp. 267–276.

Cailteux, J., 1978a. Particularités stratigraphiques et pétrographiques du faisceau inférieur du Groupe des Mines au centre de l'Arc cuprifère shabien. Annales de la Société Géologique de Belgique 100 (1977), 55–71.

Cailteux, J., 1978b. La succession stratigraphique du C.M.N. (ou R-2.3) au centre de la sous-province cuprifère shabienne. Annales de la Société Géologique de Belgique 100 (1977), 73–85.

Cailteux, J., 1979. L'origine du talc dans le C.M.N. (ou R.2.3) de Kambove (Shaba-Zaïre). Annales de la Société Géologique de Belgique 102, 213–221.

Cailteux, J., 1983. Le Roan shabien dans la région de Kambove (Shaba-Zaïre). Etude sédimentologique et métallogénique. Thèse de Doctorat en Sciences Appliquées, University of Liège (Belgium), 232 p.

Cailteux, J., 1986. Diagenetic sulphide mineralization within the stratiform copper–cobalt deposit of West Kambove (Shaba-Zaïre). In: Friedrich, G.H., Genkin, A.D., Naldrett, A.J., Ridge, J.D., Sillitoe, R.H., Vokes, F.M. (Eds.), Geology and Metallogeny of Copper Deposits, Part IV, Sediment-Hosted Deposits. 27th International Geological Congress, Moscow (1984), Special Publication 4, Society for Geology Applied to Mineral Deposits. Springer-Verlag, Heidelberg, pp. 398–411.

Cailteux, J., 1994. Lithostratigraphy of the Neoproterozoic Shaba-type (Zaire) Roan Supergroup and metallogenesis of associated stratiform mineralization. In: Kampunzu, A.B., Lubala, R.T. (Eds.), Neoproterozoic Belts of Zambia, Zaire and Namibia. Journal of African Earth Sciences 19, 279–301.

Cailteux, J., 1997. Minéralisations à U–Pb–Se–Mo–Ni dans le gisement stratiforme cupro-cobaltifère de Kambove-Ouest (Shaba, Rép.Zaïre). In: Charlet, J.-M. (Ed.), Colloque International Cornet, Gisements stratiformes de cuivre et minéralisations associées, Mons (1994). Académie Royale des Sciences d'Outre-Mer, 245–268.

Cailteux, J. 2003. Proterozoic sedimentary-hosted base-metal deposits of Western Gondwana. Conference and Field Workshop, Lubumbashi, 223 p.

Cailteux, J., Binda, P.L., Katekesha, W.M., Kampunzu, A.B., Intiomale, M.M., Kapenda, D., Kaunda, C., Ngongo, K., Tshiauka, T., Wendorff, M., 1994. Lithostratigraphical correlation of the Neoproterozoic Roan Supergroup from Shaba (Zaire) and Zambia, in the central African copper–cobalt metallogenic province. In: Kampunzu, A.B., Lubala, R.T. (Eds.), Neoproterozoic Belts of Zambia, Zaire and Namibia. Journal of African Earth Sciences 19, 265–278.

Cailteux, J., Dimanche, F., 1973. Examen des oxydes de fer et titane dans l'environnement du gisement de cuivre de Musoshi (Shaba, rép. du Zaïre). Bulletin de la Société française de Minéralogie et de Cristallographie 96, 378–382.

Cailteux, J., Kampunzu, A.B., 1995. The Katangan tectonic breccias in the Shaba province (Zaire) and their genetic significance. In: Wendorff, M., Tack, L. (Eds.), Late Proterozoic Belts in Central Africa. Musée Royal de l'Afrique Centrale, Tervuren, Belgique. Annales des Sciences Géologiques, vol. 101, pp. 63–76.

Cailteux, J., Kampunzu, A.B., Batumike, M.J., this volume. Lithostratigraphic position and petrographic characteristics of R.A.T. ("Roches Argilo-Talqueuses") Subgroup, Neoproterozoic Katangan Belt (Congo). Journal of African Earth Sciences, doi:10.1016/j.jafrearsci.2005.08.011.

Cailteux, J., Lefebvre, J.-J., 1975. Stratigraphie et minéralisation du gisement cuprifère de Kipapila, Shaba, Zaïre. Annales de la Société Géologique de Belgique 98, 317–330.

Caron, J.P.H., Kampunzu, A.B., Lwango, L.B., Kanika, W.R., 1986. Les ressources minérales d'âge protérozoïque moyen en Afrique Centrale et l'évolution "tectonique" de la chaîne kibarienne. UNESCO, Geology for Economic Development, Newsletter 5, 139–152.

Claypool, G.E., Holser, W.T., Kaplan, I.R., Sakai, H., Zak, I., 1980. The age curves of sulfur and oxygen isotopes in marine sulfate and their mutual interpretation. Chemical Geology 28, 190–260.

Clemmey, H., 1974. Sedimentary geology of a late Precambrian copper deposit at Kitwe, Zambia. In: Bartholomé, P. (Ed.), Gisements stratiformes et provinces cuprifères. Centenaire de la Société Géologique de Belgique, Liège, pp. 255–265.

Cluzel, D., 1986. Contribution à l'étude du métamorphisme des gisements cupro-cobaltifères stratiformes du Sud-Shaba, Zaïre. Le district minier de Luishia. Journal of African Earth Sciences 5, 557–574.

Cluzel, D., Guilloux, L., 1986. Hydrothermal character of the Shaba Cu–Co–U mineralization. The Canadian Mineralogist 24, 1.

Cosi, M., de Bonis, A., Gosso, G., Hunziker, J., Martinotti, G., Moratto, S., Robert, J.P., Ruhlman, F., 1992. Late Proterozoic thrust tectonics, high-pressure metamorphism and uranium mineralization in the Domes area, Lufilian Arc, northwestern Zambia. Precambrian Research 58, 215–240.

Craig, J.R., Vaughan, D.J., 1979. Cobalt-bearing sulfide assemblages from the Shinkolobwe deposit, Katanga, Zaire. American Mineralogist 64, 136–139.

Darnley, A.G., 1960. Petrology of some Rhodesian Copperbelt orebodies and associated rocks. Transactions of the Institution of Mining and Metallurgy (London) 69, 137–173.

Davidson, C.M., 1931. The geology and ore deposits of Chambishi, northern Rhodesia. Economic Geology 26, 131–154.

Dechow, E., Jensen, M.L., 1965. Sulfur isotopes of some central African sulfide deposits. Economic Geology 60, 894–941.

Dejonghe, L., 1995. The copper deposit of Kinsenda (SE Shaba, Zaire): a strata-bound mineralisation hosted in siliciclastic formations of the Roan (Upper Proterozoic). In: Wendorff, M., Tack, L. (Eds.), Late Proterozoic Belts in Central Africa. Musée Royal de l'Afrique Centrale, Tervuren, Belgique, Annales des Sciences Géologiques 101, 87–94.

Demesmaeker, G., François, A., Oosterbosch, R., 1963. La tectonique des gisements cuprifères stratiformes du Katanga. In: Lombard, J., Nicolini, P. (Eds.), Gisements stratiformes de cuivre en Afrique, 2ème partie: Tectonique. Association des Services Géologiques Africains (Paris), Lusaka 1962, 47–115.

Derriks, J.J., Vaes, J.F., 1956. Le gite d'uranium de Shinkolobwe. Actes de la Conférence Internationale sur l'utilisation de l'énergie atomique à des fins pacifiques. Géologie de l'uranium et du thorium, Nations Unies, Genève, VI, pp. 108–144.

Derriks, J.J., Oosterbosch, R., 1958. Les gites de Swambo et de Kalongwe comparés à Shinkolobwe: contribution à l'étude de l'uranium du Katanga. Deuxième Conférence Internationale sur l'utilisation de l'énergie atomique à des fins pacifiques, II, Nation Unies, Genève, pp. 623–695.

De Waele, B., Mapani, B., 2002. Geology and correlation of the central Irumide belt. Journal of African Earth Sciences 35, 385–397.

Dimanche, F., 1974. Paragenèse des sulfures de cuivre dans les gisements du Shaba (Zaïre): I. Kipushi; II. Kamoto. In: Bartholomé, P. (Ed.), Gisements stratiformes et provinces cuprifères. Centenaire de la Société Géologique de Belgique, Liège, pp. 185–201.

Drysdall, A.R., Johnson, R.L., Moore, T.A., Thieme, J.C., 1972. Outline of the geology of Zambia. Geologie en Mijnbouw 51, 265–276.

du Trieu de Terdonck, R., 1956. Géologie et recherches minières. In: Cuypers, L. (Ed.), Union Minière du Haut-Katanga 1906–1956, Evolution des techniques et des activités sociales, Bruxelles, pp. 11–68.

François, A. 1973. L'extrémité occidentale de l'Arc cuprifère shabien. Etude Géologique, Gécamines, Likasi (Shaba-Zaïre), 120 p.

François, A., 1974. Stratigraphie, tectonique et minéralisations dans l'Arc cuprifère du Shaba (Rép.du Zaïre). In: Bartholomé, P. (Ed.), Gisements stratiformes et provinces cuprifères. Centenaire de la Société Géologique de Belgique, Liège, pp. 79–101.

François, A., 1987. Synthèse géologique sur l'Arc cuprifère du Shaba (Rép.du Zaïre). Société Belge de Géologie, Centenaire 1987, pp. 15–65.

François, A., 1995. Problèmes relatifs au Katanguien du Shaba. In: Wendorff, M., Tack, L. (Eds.), Late Proterozoic Belts in Central Africa. Musée Royal de l'Afrique Centrale, Tervuren, Belgique. Annales des Sciences Géologiques 101, 1–20.

François, A., Cailteux, J., 1981. La couverture katangienne entre les socles de Zilo et de la Kabompo, République du Zaïre, Région de Kolwezi. Musée Royal de l'Afrique Centrale, Tervuren, Belgique. Annales des Sciences Géologiques 87, 1–50.

François, A., Oosterbosch, R., 1968. Etudes géologiques récentes dans le Katanga méridional. In: Association des Services Géologiques Africains, Commission du Congrès Géologique International, Progrès dans la reconnaissance géologique des pays africains, Réunion de Prague, Katanga, pp. 1–11.

Freeman, P.V. 1988a. Description of some mineral deposits discovered or re-investigated in the post world war II period. Unpublished report, Lusaka.

Freeman, P.V. 1988b. Description of mineral deposits on the Copperbelt (and Kabwe, Nampundwe). Unpublished report, Lusaka.

Garlick, W.G., 1940. Problem of the granites and origin and location of the copper deposits of the Nkana Concession. Unpublished report, Rhokana Corporation.

Garlick, W.G., 1945. Zonal theory of sedimentary uranium-copper-cobalt pyrite deposits. Unpublished report, Rhokana Corporation.

Garlick, W.G., 1961a. Structural evolution of the Copperbelt. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 89–105.

Garlick, W.G., 1961b. The Syngenetic Theory. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 146–165.

Garlick, W.G., 1961c. Chambishi. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 281–297.

Garlick, W.G., 1964. Criteria for recognition of syngenetic sedimentary mineral deposits and veins formed by their remobilisation. In: Proceedings Australian Institution Mining Metallurgy, pp. 1–25.

Garlick, W.G., 1967. Special features and sedimentary facies of stratiform sulphide deposits in arenites. In: Proceedings of the 15th Conference of the Institute of Geology, University of Leicester, pp. 107–169.

Garlick, W.G., 1989. Genetic interpretation from ore relations to algal reefs in Zambia and Zaire. In: Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C., Kirkham, R.V. (Eds.), Sediment-hosted stratiform copper deposits. Geological Association of Canada, Special Paper, vol. 36, pp. 471–498.

Garlick, W.G., Fleischer, V.D., 1972. Sedimentary environment of Zambian copper deposition. Geologie en Mijnbouw 51, 277–298.

Gray, A., 1929. The outline of the geology and ore deposits of the Nkana concession. In: 15th International Geological Congress.

Greyling, L.N., Yao, Y., Robb, L.J., Master, S., 2002. Contribution to the geology and mineralization of the central Africa Copperbelt: III-nature of metamorphic and epigenetic fluids. In: 11th Quadrennial IAGOD Symposium and Geocongress 2002. Extended Abstracts on CD-ROM, Windhoek (Namibia), 4 pp., unpaginated.

Grujenschi, C., 1979. Quelques observations sur la position stratigraphique de la "Série des Mines" au Shaba. Annales de la Société Géologique de Belgique 101 (1978), 1–11.

Haynes, D.W., 1986. Stratiform copper deposits hosted by low-energy sediments. II. Nature of source rocks and composition of metal-transporting water. Economic Geology 81, 226–280.

Hitzman, M.W., 2000. Source basins for sediment-hosted stratiform copper deposits—implications for the structure of the Zambian Copperbelt. Journal of African Earth Sciences 30, 855–863.

Hoy, L.D., Ohmoto, H., 1989. Constraints for the genesis of redbed-associated stratiform Cu deposits from sulphur and carbon mass-balance relations. In: Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C., Kirkham, R.V. (Eds.), Sediment-hosted stratiform copper deposits. Geological Association of Canada, Special Paper, vol. 36, pp. 135–148.

Jackson, G.C.A., 1932. The geology of the Nchanga district. Journal of Geological Society of London 88, 443–514.

Jedwab, J., 1997. Minéralogie des métaux du groupe du platine au Shaba, Zaïre. In: Charlet, J.-M. (Ed.), Colloque International Cornet, Gisements stratiformes de cuivre et minéralisations associées, Mons (1994). Académie Royale des Sciences d'Outre-Mer, pp. 325–355.

Jensen, M.L., Dechow, E., 1962. The bearing of sulfur isotopes on the origin of the Rhodesian copper deposits. Transactions of the Geological Society of South Africa 61, 1–17.

John, T., Schenk, V., Haase, K., Scherer, E., Tembo, F., 2003. Evidence for a Neoproterozoic ocean in south central Africa from MORB-type geochemical signatures and P–T estimates of Zambian eclogites. Geology 31, 243–246.

Jordaan, J., 1961. Nkana. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 297–328.

Kampunzu, A.B., Cailteux, J., 1999. Tectonic evolution of the Lufilian Arc during Neoproterozoic pan African orogenesis. Gondwana Research 2, 401–421.

Kampunzu, A.B., Cailteux, J.L.H., Moine, B., Loris, H.N.B.T., this volume. Geochemical characterisation, provenance, source and depositional environment of "Roches Argilo-Talqueuses" (R.A.T.) and Mines Subgroups sedimentary rocks in the Neoproterozoic Katangan Belt (Congo): lithostratigraphic implications Journal of African Earth Sciences, doi:10.1016/j.jafrearsci.2005.08.003.

Kampunzu, A.B., Kanika, M., Kapenda, D., Tshimanga, K., 1993. Geochemistry and geotectonic setting of late Proterozoic Katangan basic rocks from Kibambale in central Shaba (Zaire). Geologische Rundschau 82, 619–630.

Kampunzu, A.B., Kapenda, D., Manteka, B., 1991. Basic magmatism and geotectonic evolution of the Pan African belt in central Africa: evidence from the Katangan and West Congolian segments. Tectonophysics 190, 363–371.

Kampunzu, A.B., Tembo, F., Matheis, G., Kapenda, D., Huntsman-Mapila, P., 2000. Geochemistry and tectonic setting of mafic igneous units in the Neoproterozoic Katangan basin, central Africa: implications for Rodinia break up. Gondwana Research 3, 125–153.

Kapenda, D., Kampunzu, A.B., Cabanis, B., Namegabe, M., Tshimanga, K., 1998. Petrology and geochemistry of post-kinematic mafic rocks from the Palaeoproterozoic Ubendian belt, NE Katanga (Democratic Republic of Congo). Geologische Rundschau 87, 345–362.

Katekesha, W.M., 1975. Conditions de formation du gisement cupro-cobaltifère de Kamoto Principal (Shaba-Zaïre). Thèse de Doctorat en Sciences, University of Liège (Belgium), 237 p.

Key, R.M., Liyungu, A.K., Njamu, F.M., Somwe, V., Banda, J., Mosley, P.N., Armstrong, R.A., 2001. The western arm of the Lufilian Arc in NW Zambia and its potential for copper mineralisation. Journal of African Earth Sciences 33, 503–528.

Krouse, H.R., 1980. Sulfur isotopes in our environments. In: Fontes, J.C., Frits, P. (Eds.), Isotope Geochemistry, The Terrestrial Environment, vol. 1. Elsevier, Amsterdam, pp. 435–471.

Lee-Potter, J.B., 1961. Baluba. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 343–351.

Lefebvre, J.J., 1974. Mineralisations cupro-cobaltiferes associées aux horizons pyroclastiques situés dans le faisceau supérieur de la Serie de Roan, à Shituru, Shaba, Zaire. In: Bartholomé, P. et al. (Eds.), Gisements stratiformes et provinces cuprifères. Société Géologique de Belgique, Liège, pp. 103–122.

Lefebvre, J.-J., 1976a. Phénomènes post-diagénétiques dans l'écaille Nord-Est du gisement de Kabolela, Shaba, Zaïre. Bulletin de la Société Belge de Géologie 85, 7–29.

Lefebvre, J.-J., 1976b. Minéralisation cupro-cobaltifère et zincifère d'aspect épigénétique à Kabolela, Shaba, Zaïre. Annales de la Société Géologique de Belgique 99, 315–335.

Lefebvre, J.-J., 1979. Le Groupe de Mwashya: mégacyclothème terminal du Roan (Shaba, Zaïre Sud-Oriental), I—approche lithostratigraphique et étude de l'environnement sédimentaire. Annales de la Société Géologique de Belgique 101 (1978), 209–225.

Lefebvre, J.-J., 1989. Depositional environment of copper–cobalt mineralization in the Katangan sediments of Southeast Shaba, Zaire. In: Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C., Kirkham, R.V. (Eds.), Sediment-hosted stratiform copper deposits. Geological Association of Canada, Special Paper, vol. 36, pp. 401–426.

Lefebvre, J.-J., Cailteux, J., 1975. Volcanisme et minéralisations diagénétiques dans le gisement de l'Etoile (Shaba-Zaïre). Annales de la Société Géologique de Belgique 98, 177–195.

Lefebvre, J.-J., Patterson, L.E., 1982. Hydrothermal assemblage of aluminian serpentine, florencite and kyanite in the Zairean Copperbelt. Annales de la Société Géologique de Belgique 105, 51–71.

Lefebvre, J.-J., Tshiauka, T., 1986. Altérations associées à la minéralisation uranifère de Musoshi (Shaba, Zaïre). Annales du Musée Royal de l'Afrique Centrale, Tervuren (Belgique) 92, 1–63.

Lerouge, C., Cailteux, J., Kampunzu, A.B., Milési, J.P., Fléhoc, C., 2004. Preliminary sulfur isotope data of the Luiswishi ore deposit, RDC. In: CAG20, Colloquium of African Geology, 20th, Orléans, France, pp. 261.

Loris, N.B.T., 1996. Etude des minéralisations uranifères du gisement cupro-cobaltifère de Luiswishi (Shaba, Zaïre): contextes géologiques et géochimiques. Discussion des modèles génétiques. Thèse de Doctorat en Sciences Appliquées, Polytechnic Faculty of Mons (Belgium), 374 p.

Loris, N.B.T., Charlet, J.-M., Pechman, E., Clare, C., Chabu, M., Quinif, Y., 1997. Caractéristiques minéralogiques, cristallographiques, physico-chimiques et âges des minéralisations uranifères de Luiswishi (Shaba, Zaïre). In: Charlet, J.-M. (Ed.), Colloque International Cornet, Gisements stratiformes de cuivre et minéralisations associées, Mons (1994). Académie Royale des Sciences d'Outre-Mer, pp. 285–306.

Loris, N.B.T., Charlet, J.-M., Okitaudji, R., 2002. La mobilité de l'uranium et des métaux associés en environnement géologique oxydo-réducteur, le cas des minéralisations Cu–Co–Ni–U de Luiswishi (Katanga, RDC). Bulletin des Séances de l'Académie Royale des Sciences d'Outre-Mer 48, 165–188.

Madi, L., 1985. Le Roan inférieur détritique: ensemble sédimentaire fluviatile à la base du Katanguien au Shaba. Ph.D. Thesis, Université de Lubumbashi (Zaïre), 200 p.

Manteka, B., Lubala, R.T., Kapenda, D., Caron, J.P., Kampunzu, A.B., 1985. Caractère et signification géotectonique des formations magmatiques basiques affleurant à Kibambale (Shaba, Zaïre). Comptes Rendus de l'Académie des Sciences, Paris 301, 171–176.

Malan, S.P., 1964. Stromatolites and other algal structures at Mufulira, northern Rhodesia. Economic Geology 59, 397–415.

Massone, H.J., Wilher, A.P., Kampunzu, A.B., 1994. P-T evolution of late Proterozoic eclogites and their geodynamic implications. In: Proterozoic Crustal and Metallogenic Evolution. International Conference, Geological Society and Geological Survey of Namibia (Abstract volume), pp. 46.

McGowan, R.R., Roberts, S., Foster, R.P., Boyce, A.J., Coller, D., 2003. Origin of the copper–cobalt deposits of the Zambia Copperbelt: An epigenetic view from Nchanga. Geology 31 (6), 497–500.

McKinon, D.M., Smit, N.J., 1961. Nchanga. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 234-275.

Mendelsohn, F., 1961a. Katanga system. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 41–54.

Mendelsohn, F., 1961b. Metamorphism. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 106–116.

Mendelsohn, F., 1961c. Ore genesis; summary of the evidence. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 130–146.

Mendelsohn, F., 1961d. Roan Antelope. In: The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 351–405.

Misi, A., Iyer, S., Silva Coelho, C., Tassinari, C., Franca-Rocha, W., Rocha Gomes, A., Toulkeridis, I., Sanches, A., 2000. A metallogenic evolution model for the lead-zinc deposits of the meso and Neoproterozoic sedimentary basins of the Sao Francisco Craton, Bahia and Minas Gerais. Brazil. Revista Brasileira de Geosciencias 30, 302–305.

Moine, B., Guilloux, L., Audeoud, D., 1986. Major element geochemistry of the host rocks in some sediment-hosted copper deposits. In: Friedrich, G.H., Genkin, A.D., Naldrett, A.J., Ridge, J.D., Sillitoe, R.H., Vokes, F.M. (Eds.), Geology and Metallogeny of Copper Deposits, Part IV, Sediment-Hosted Deposits, Special Publication 4, Society for Geology Applied to Mineral Deposits, Moscow 1984. Springer-Verlag, Berlin, Heidelberg, pp. 443–460.

Ngongo, K., 1975a. La dolomie stromatolitique "R.S.C." dans les gisements cuprifères stratiformes du Shaba-Zaïre. Annales de la Société Géologique de Belgique 98, 307–315.

Ngongo, K., 1975b. Sur la similitude entre les gisements uranifères (type Shinkolobwe) et les gisements cuprifères (type Kamoto) au Shaba, Zaïre. Annales de la Société Géologique de Belgique 98, 449–462.

Ngoyi, K., Dejonghe, L., 1997. Géologie et genèse du gisement stratoïde cuprifère de Kimenda (SE du Shaba, Zaïre). Bulletin de la Société Belge de Géologie 104, 245–281.

Okitaudji, L.R., 1989. Géologie sédimentaire et concentration syndiagénétique du cuivre et du cobalt dans la série des Mines du Shaba, Zaïre. Thèse de Doctorat en Sciences. Polytechnic National Institute of Lorraine (France), 476 p.

Ohmoto, H., Rye, R.O., 1979. Isotopes of Sulfur and Carbon. In: Barnes, H., Wiley, J., Sons (Eds.), Geochemistry of Hydrothermal Ore Deposits, New York.

Oosterbosch, R., 1950. La Série des Mines dans le Polygone de Fungurume. Comité Spécial du Katanga, Bruxelles 14, 1–18.

Oosterbosch, R., 1951. Copper mineralization in the Fungurume region, Katanga. Economic Geology 46, 121–148.

Oosterbosch, R., 1962. Les minéralisations dans le système de Roan au Katanga. In: Lombard, J., Nicolini, P. (Eds.), Gisements stratiformes de cuivre en Afrique, 1ère partie, Copenhagen, 1960. Association des Services Géologiques Africains, Paris, pp. 71–136.

Pirmolin, J., 1970. Inclusions fluides dans la dolomite du gisement stratiforme de Kamoto (Katanga Occidental). Annales de la Société Géologique de Belgique 93, 193–202.

Rainaud, C., Master, S., Armstrong, R.A., Robb, L.J., 2003. A cryptic Mesoarchaean terrane in the basement to the central African Copperbelt. Journal of the Geological Society London 160, 11–14.

Rainaud, C., Master, S., Robb, L.J., Armstrong, R.A., 1999. A fertile Palaeoproterozoic magmatic arc beneath the central African Copperbelt. In: Stanley, C.J. et al. (Eds.), Mineral Deposits: Processes to Processing. Balkema, Rotterdam, pp. 1427–1430.

Renfro, A.R., 1974. Genesis of evaporite-associated stratiform metalliferous deposits. A sabkha process. Economic Geology 69, 33–45.

Reynolds, D.G. 1959. Sedimentary structures in the ore formation. Rhokana Corporation, Unpublished report.

Richards, J.P., Krogh, T.E., Spooner, E.T.C., 1988. Fluid inclusion characteristics and U–Pb rutile age of late hydrothermal alteration and veining at Musoshi stratiform copper deposit, central African Copperbelt, Zaire. Economic Geology 83, 118–139.

Rose, A.W., 1989. Mobility of copper and other heavy metals in sedimentary environments. In: Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C., Kirkham, R.V., (Eds.), Sediment-Hosted Stratiform Copper Deposits. Geological Association of Canada, Special Paper, vol. 36, pp. 97–110.

Schwellnus, J.E.G., 1961. Bancroft. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 214–234.

Sebagenzi, M.N., 1993. Etude gravimétrique et géothermique du Sud-Est du Zaïre et du Nord de la Zambie (Afrique centrale). Thèse de Doctorat en sciences, University of Paris 7, 272p.

Sebagenzi, M.N., 1997a. Gravity modelling of the lithosphere in Southeastern Zaire and Zambia (central Africa). African Geosciences Review 4, 153–175.

Sebagenzi, M.N., 1997b. Signification tectonique du couple d'anomalies gravimétriques négative-positive de la chaîne katanguienne (Néoprotérozoïque) du Sud-Est du Zaïre et du Nord de la Zambie (Afrique centrale): interprétation préliminaire. Annales de la Société Géologique de Belgique 120, 161–174.

Schneiderhöhn, H., 1931. Mineralische Bodenschätze im südlichen Afrika. NEM-Verlag, Berlin, 111 p.

Schneiderhöhn, H., 1932. The geology of the Copperbelt, northern Rhodesia. Mining Magasine 46, 241–245.

Schneiderhöhn, H., 1937. Die Kupferlagerstätten von Nord Rhodesia und Katanga. Geologische Rundschau 28, 282–291.

Smit, N.J., 1961. Mimbula. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 275–280.

Steven, N.M., 2000. A Shaba-type Cu–Co(–Ni) deposit at Luamata, West of the Kapompo Dome, northwestern Zambia. Exploration Mining Geology 9, 277–287.

Steven, N.M., Armstrong, R., 2003. A metamorphosed Proterozoic carbonaceous shale-hosted Co–Ni–Cu deposit at Kalumbila, Kabompo Dome: the Copperbelt ore shale in northwestern Zambia. Economic Geology 98, 893–909.

Sweeney, M.A., 1987. The use of fluid inclusion geochemistry in determining the origin of veins, examples from the Zambian Copperbelt. Journal of Geological Society of Zambia 1, 18–28.

Sweeney, M.A., Binda, P.L., 1989a. Mineralization controls and source of metals in the Lufilian Fold Belt, Shaba (Zaïre), Zambia, and Angola—a discussion. Economic Geology 84, 963–964.

Sweeney, M.A., Binda, P.L., 1989b. The role of diagenesis in the formation of the Konkola Cu–Co ore-body of the Zambian Copperbelt. In: Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C., Kirkham, R.V. (Eds.), Sediment-Hosted Stratiform Copper Deposits. Geological Association of Canada, Special Paper, vol. 36, pp. 499–518.

Sweeney, M.A., Binda, P.L., 1994. Some constraints on the formation of the Zambian Copperbelt deposits. In: Kampunzu, A.B., Lubala, R.T. (Eds.), Neoproterozoic Belts of Zambia, Zaire and Namibia. Journal of African Earth Sciences 19, 303–313.

Sweeney, M.A., Turner, P., Vaughan, D.J., 1986. Stable isotope and geochemical studies of the role of early diagenesis in ore formation, Konkola basin, Zambian Copperbelt. Economic Geology 81, 1838–1852.

Sweeney, M.A., Turner, P., Vaughan, D.J., 1987. The Marie Slate: a model for the precipitation of calcite, dolomite and sulphides in a newly formed anoxic sea. Sedimentology 34, 31–48.

Sweeney, M.A., Binda, P.L., Vaugham, D.J., 1991a. Genesis of the ore of the Zambian Copperbelt. Ore Geology Reviews 6, 51–76.

Sweeney, M.A., Vaugham, D.J., Binda, P.L., 1991b. The geochemistry of the basement complex of the Zambian Copperbelt. Implications for mineralization. In: Pagel, M., Leroy, J.L. (Eds.), Source, Transport and Deposition of Metals. 25th Anniversary Meeting of Société de Géologie Appliquée. Nancy. France. Balkema. pp. 359–362.

Tembo, F., 1994. The geology, geochemistry and tectonic significance of metagabbroic rocks in the Lufilian Arc of Zamibia. Ph.D. Thesis, University of Gottingen, Cuvillier Verlag Gottingen, Germany, 118 p.

Tshiauka, T., 2001. Potentiel géologique et reserves Sodimico; gisement de Lubembe. Sodimico, Unpublished report.

Tshiauka, T., Katekesha, W.M., Cailteux, J., Intiomale, M.M., Kampunzu, A.B., Kapenda, D., Chabu, M., Ngongo, K., Mutombo, K., Nkanika, W.R., 1995. Lithostratigraphy of the Neoproterozoic Katangan sedimentary sequences in the Musoshi Copper District (SE Shaba, Zaire) and incidences on copper and cobalt economic geology in central Africa. In: Wendorff, M., Tack, L. (Eds.), Late Proterozoic Belts in Central Afrika. Musée Royal de l'Afrique Centrale, Tervuren, Belgique. Annales des Sciences Géologiques 101, 29–48.

Thoreau, J., du Trieu de Terdonck, R., 1952. Le gite d'uranium de Shinkolobwe-Kasolo. Mémoire de l'Institut Royal Colonial Belge, Sciences Naturelles et Médicales II, p. 1.

Unrug, R., 1988. Mineralization control and source of metals in the Lufilian Fold Belt. Shaba (Zaire). Zambia, and Angola. Economic geology 83, 1247–1258.

Unrug, R., 1989. Mineralization control and source of metals in the Lufilian Fold Belt, Shaba (Zaire), Zambia, and Angola—a reply. Economic Geology 84, 963–970.

Vaes, J.F., 1962. A study of the metamorphism of the Roan sediments at the Musoshi copper deposit and its consequences. Musée Royal de l'Afrique Centrale, Tervuren, Belgique. Annales des Sciences Géologiques 43, 1–30.

Van Eden, J.G., 1974. Depositional and diagenetic environment related to sulfide mineralization, Mufulira, Zambia. Economic Geology 69, 59–79.

Van Eden, J.G., Binda, P.L., 1972. Scope of stratigraphic and sedimentologic analysis of the Katanga Sequence, Zambia. Geologie en Mijnbouw 51, 321–328.

Voet, H.W., Freeman, P.V., 1972. Copper orebodies in the Lower Roan metasediments at the Chingola open pit area. Zambian Copperbelt. Geologie en Mijnbouw 51, 299–308.

Walker, T.R., 1989. Application of diagenetic alterations in red beds to the origin of copper in stratiform copper deposits. In: Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C. and Kirkham, R.V. (Eds.), Sediment-hosted stratiform copper deposits. Geological Association of Canada, Special Paper, vol. 36, pp. 85–96.

Wendorff, M., 2000a. Genetic aspects of the Katangan megabreccias: Neoproterozoic of central Africa. Journal of African Earth Sciences 30, 703–715.

Wendorff, M., 2000b. Revision of the stratigraphical position of the "Roches Argilo-talqueuses" (R.A.T.) in the Neoproterozoic Katangan Belt, south Congo. Journal of African Earth Sciences 30, 717–726.

Winfield, O., 1961. Chibuluma. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. Macdonald, London, pp. 328–342.