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 40 Mt copper and 6 Mt cobalt and including several world-class deposits (> 10 Mt copper). The origin of Cu–Co mineralisation in this province remains speculative, with the debate centred around syngentic-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 allolithic 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 hosted along the southern structural block of the Lufilian Arc. The predominately allochthonous Zambian facies, exposed in Zambia and in SE Congo, forms para-autochthonous sedimentary units hosting ore deposits characterized by lower Co/Cu ratios (average 1:57). Transitional lithofacies in Zambia (e.g. Bubula, Mwindo) and in Congo (e.g. Lubembe) indicate a gradual transition in the Katangan basin during the deposition of laterally correlatable 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. Primarily 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 syngentic, 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 Bangwelu block and subsidiary Cu–Co–Ni deposits/occurrences in the Archaean rocks of the Zimbabwe craton. These two sources contain low grade ore deposits porphyry the peculiar metal association (Cu, Co, Ni, U, Cr, As, 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 syngenic 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 straddles 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 copper and includes world-class Cu–Co deposits, e.g., Kolwezi, Tenke-Fungurume, Kankola-Chililabombwe, Nchanga, Nkana, Mufumbira, 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 Glencore 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, Sb, 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 metallurgical hypotheses were proposed to explain the primary source of metals and the mineralisation process. The historical review of those 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 mineralising 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, 1972; Thorau and da Cunha de Macedo, 1952; Dernitski and Vees, 1956; Dernitski and Oosterboch, 1958; Durney, 1960; Vees, 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 unconfirmable erosional contact occurs between the granitoids and the overlying Katangan sedimentary succession in Zambia (Garlick, 1963a; Binda, 1975). This is supported by U-Pb zircon geochronological data (Armstrong et al., 1999; Rainaud et al., 1999; De Waale and Mapani, 2002) indicating that the granitoids exposed in the Copperbelt and surrounding areas are older than the Katangan sedimentary succession, i.e. Paleoproterozoic (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 syngentic theory linked the deposition of metals to the deposition of host-sediments (Schneiderhöhn, 1931, 1932, 1937; Garlick, 1945, 1960b, 1967, 1989). Metals were sourced from continental erosion and transported in solution by rivers to the sedimentary deposits. 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 (before sulphides 1) 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, 1961, 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 mineralising fluids to late diagenetic hydrothermal fluids of undefined origin (Cluzel and Guillon, 1986) or originating from mafic igneous rocks or rift-related processes (Annels, 1974a, 1974b, 1979; Annels and Simmonds, 1984; Lefebvre, 1989; Utrug, 1988). Cailliaux et al. (1994) showed that stratiform copper-cobalt orebodies in Zambia and Congo are hosted in laterally continuous 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 mineralising processes.

2. Geologic 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 Mwinkela in the west (e.g. Brock, 1961; Steven, 2000), to Kolwezi in the northwest, up to Luanshya (previously Roan Annelope) and Lusishi in the southeast of the belt (Fig. 2). It is commonly assumed that this copper...
<table>
<thead>
<tr>
<th>Group</th>
<th>Subgroup</th>
<th>Formation</th>
<th>Lithology</th>
<th>Formation</th>
<th>Subgroup</th>
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<td>Dolomitic shales grey to black</td>
<td>Moshiyo</td>
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<tr>
<td></td>
<td></td>
<td>Lower 3.4.1</td>
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<td>vertebrates</td>
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<td></td>
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<td></td>
<td>R.2</td>
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<td>Dolomitic, sandstones, dolomitic shales sandstones</td>
<td>Dolomitic shales, grey to black</td>
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*Note: Lithology and formation codes are based on the results of the R.A.T. sequence and are consistent with previous studies.*
The Katangan supracrustal sedimentary succession is ~5–10 km thick and commonly subdivided 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; Baffard, 1988; Cailette, 1994; Cailette et al., 1994), and volcanic and plutonic mafic rocks emplaced in a continental rift (Kampuzu et al., 2000 and references therein). The Nguba supracrustal assemblage is made up of siliciclastic and carbonate sedimentary rocks (François, 1974; Baffard, 1988) and includes mafic igneous rocks emplaced in a proto-oceanic rift similar to the Red Sea (Kampuzu et al., 1991, 1993; Mantoko et al., 1993; Kapenda et al., 1998). Kundelungu sedimentary rocks represent syn- to post-orogenic sedimentary deposits (Kampuzu and Cailette, 1999).

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

Fig. 2. Location of the main stratiform Cu-Co deposit in the central African Copperbelt (KA = Kafue Anircline; modified from François (1974) and Cailette (1994).
The tabular-shaped Kandelungu is a continentallastic molasse sequence extending into the lower Palaeozoic (Kimpunzu and Caileux, 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), Ngba and folded Kandelungu (exclusively unare kungutungu) sedimentary rocks are part of a Late Triassic to Cretaceous sheet. The Mwasha Subgroup rocks conformably overlie the lower Roan rocks (Caileux et al., 1994), and are conformably overlain by the Grand Congolais (Table 1).

Grujenschi (1979) and Wendorff (2000a) interpreted occurrences of megabreccias in the Katangan succession as sedimentary synvolcanic conglomerates (olistostromes), and Wendorff (2000b) further questioned the lithostrophic succession of the Roan Group. Although the existence of synvolcanic 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. Caileux et al., this volume; Kampuzni et al., this volume). In all cases, the debate on the lithostrophic nature of the Katangan is outside the objectives of this paper, and only the common lithostrophic position of the Mines Subgroup and related sediments is discussed further below.

The stratiform Copperbelt copper-cobalt orebodies occur in the Roan Group (i.e. in Mines and Mwasha Subgroups; Table 1). The Roan Group sedimentary rocks display a marked lateral variation of facies between Zambian-type and Congo-type successions. In Zambia and SE-Congo, deposits are mainly hosted in parautochthonous siliciclastic rocks close to basement terrains. The main ore deposits define two parallel trends, north-east and south-west of the Katanga saddle (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 fluviolacustrine sedimentary rocks rest unconformably on the pre-Katangan basement (Moundahom, 1961a; Binda and Mulgrew, 1974). In Congo, Cu-Cob deposits and their host rocks define thrust sheets, nappes and klippen formed during the Lufilian Orogeny (Demessamra et al., 1983; Caileux and Kampuzni, 1995; Kampuzni and Caileux, 1999). The dominant lithological units are dolomites and dolomitic shales (Oosterhosh, 1962; Demessamra et al., 1963; François, 1974, 1987; Caileux, 1994).

The lowest formations of the Roan Group (R.A.T.—— “Roches Argile-Talpues”—and Minda Subgroups; Table 1) were deposited in an oxic environment. In Zambia, the Minda Subgroup includes (Binda, 1994; Caileux et al., 1994; Tumaia et al., 1997): a sandstone-boulder conglomerate at the base (Chimpufi Formation), followed by aeolian quartzites (Katufya Formation) and by immature braided stream/alluvial fan conglomerates, arkoses and upward-fining sandstone sequences (Mutanda Formation). In Congo, the base of the R.A.T. Subgroup is unknown (François, 1974), but a boulder conglomerate, probably correlatable of the Chimufi Formation, occurs at Nzilo above the Kabarang basement. R.A.T. sedimentary rocks, laterally correlating of the Mutanda Formation (Caileux et al., 1994), include red chlorite-rich dolomitic silts, dolomitic fine-grained sandstones, silty dolomites and dolomitic silt dolomites (Oosterhosh, 1950; Katokeshi, 1975; Caileux, 1978a, 1982, 1995).

Wendorff (2000b) claims that Red and Grey R.A.T. are synvolcanic sedimentary rocks younger than the Roan Group and deposited in the Katangan foreland basin after the deposition of the Nea Group. However, field observations and geochemical data invalidate this interpretation (Caileux et al., this volume; Kampuzni et al., this volume). Furthermore, the same author suggested that the Nzilo conglomerate is part of the Mwasha 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 siliciclastic environment. They include a succession of arkoses, silts, sandy argillites and shales exposed north of the Katfi “Artéline” (Zambia), dolomitic shales and dolomites in Congo and south of the Katfi “Artéline” in Zambia (Bartholomé et al., 1977; Annona, 1978; Binda and Mulgrew, 1974; Caileux, 1978a, 1994; Caileux et al., 1994; Tumaia et al., 1995). A carbonate unit marks the top of the latterly correlatable 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 (Garlic, 1948; Reynolds, 1959; Mendelsohn, 1961; François, 1973; Katokeshi, 1975; Caileux, 1983; Caileux and Kampuzni, 1995).

The laterally correlatable Kirihumbwa (Zambia) and Diopsite (Congo) Subgroups display strong deformation, e.g. the lithological succession includes arkoses, conglomerates, silts, dolomitic shales, dolomites, and these lithologies show a similar succession. The Mwasha Subgroup is characterised by platform carbonates in the Lower Mwasha grading to more open marine dolomitic shales, black shales or sandstones in the Upper Mwasha. Gabbros intruding the Upper Roan without formations (but not the Mwasha Subgroup) and mafic lavas and pyroclastic rocks in the Lower Mwasha belong to a single syn-Lower Mwasha igneous event (Kampuzni et al., 2000) and references therein: dated at 760 ± 5 Ma by U–Pb SHRIMP technique (Key et al., 2001). The upper Mwasha is overlain by a glacial diamict, called “Grand Congolais” which starts the Nzilo succession (Cahen, 1954; Binda and Van Eden, 1972).
Table 2
Lithostratigraphy of the Mines Subgroup in Congo (modified from Praepoels [1987] and Calleux [1994])

<table>
<thead>
<tr>
<th>Sub-group</th>
<th>Formation</th>
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</table>
| Mines R-2 | Kabombe R-2.3 | Upper R-2.32 | White to pink massive dolomite and more or less tawny finely bedded dolomites, with interbedded gray to pink- red chloritic dolomitic allinites, occasional epaxiptic-type collapse breccias and interformational conglomerates. More or less carbonaceous, massive carbonates with occasional stromatolites, more or less tawny finely bedded dolomites with interbedded chloritic dolomite allinites, occasional epaxiptic-type collapse breccias and interformational conglomerates.  
Pink-brown to white massive dolomite |
|          |           | Lower R-2.3.1 | More or less carbonaceous, tawny, more or less carbonaceous, massive dolomitic allinites with occasional stromatolites; with occasional oolitic or epiphyllal beds |
|          |           |         | 3rd Oombdy (Kamshy) |
|          |           |         | (Kamshy) |
|          | S.D.-3b   | D. 3b  | Black Carbonaceous weakly dolomitic shale |
|          | S.D.-3a   | D. 3a  | Highly dolomitic shale, with occasional stromatolitic dolomite and at top or at base |
|          | S.D.-2d   | D. 2d  | Black Carbonaceous weakly dolomitic shale |
|          | S.D.-2c   | D. 2c  | Highly dolomitic shale, occasional carbonaceous shale at base |
|          | S.D.-2b   | D. 2b  | Dolomitic shale, with frequent stromatolitic dolomite bed at base |
|          | S.D.-1b (R.U.M.Z.) | D. 1b | Black Carbonaceous weakly dolomitic shale |
|          | S.D.-1a (S.D.B.) | D. 1a | Dolomitic shale, with lenticular beds and nodules pseudomorph after anhydrite |
|          |           |         | Upper Oombdy |
| Kamoto R-2.1 | R.S.C. |         | Massive, stromatolitic dolomites, with interbeded chloritic allinites |
|          | R.S.F.    |         | Silicious, finely bedded dolomites with laminitic stromatolites; interbedded dolomitic allinites in shales |
|          | D.Sтрат.  |         | More or less silty and chloritic stratified dolomites |
|          | R.A.T. gres |         | Grey chloritic-dolomitic massive allinites (up to 10 m) |

3. Lithostratigraphic control of copper-cobalt orebodies

Major primary deposits and most primary copper occurrences are stratigraphically controlled (Tables 1, 2), i.e. they occur in the Kabombe Dolomite and Dolomitic Shales Formations of the Mines Subgroup in Congo (Oosterbosch, 1962; Calleux, 1994 and references therein), and in lateral equivalents known as the Ore Shale Formation (Binda and Mulemwe, 1974; Calleux 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. Katanga-Nord; Fig. 3) to several kilometres (e.g. Dikulwile-Mashamba at Kolwezi; Luanshya in Zambia) along strike, except where they are interrupted by compressional structures related to the Lufilian orogeny (Jennessaker et al., 1968; Kampanza and Calleux, 1999). The lateral variation of sulphides in the orebodies shows copper-rich zones grading into copper-poor zones and to pyritic-high zones; e.g. Kambove-Ouest (Calleux, 1982, 1986, 1994) and Nchanga (McKinnon and Emitt, 1961).

Some Cu-(few Co) primary sulphide mineralizations occur in the Mwasha Subgroup in Congo, and also are stratigraphically controlled in dolomites of the Lower Mwasha.

3.1. Mines Subgroup Congo-type deposits

The Congo-type stratiform deposits stretch from Kolwezi up to Kinshasa (Fig. 2) and are generally characterized
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 (Bartolomé et al., 1972; Calleux, 1978a, 1983, 1994). The host rocks contain blocks, nodules and breccias of dolomite-quartz pseudomorphs after anhydrite and gypsum, and high contents of Mg, Sr, Sr, Li, B. Brescian be linked to the deposition of sediments under saline evaporitic conditions (Bartolomé et al., 1972; Katoksha, 1975; Calleux, 1978a, 1983, 1994, Moine et al., 1986).

The Lower orebody host-rocks include (Table 2): (1) a massive chalrite-dolomite silicate known as Grey R.A.T. ("Roches Argilo-Talquetes"); (2) a fine-grained stratified dolostone (D.S.r.; "Dolomie Stratifiée"); (3) shelly-stromatolitic dolomites forming limestones alternating with thin chalrite-dolomite silty beds (R.S.F., "Roches Siliceuses Feuillées"). The Upper Orebody host-rocks include (Table 2): (1) the basal Dolomites Shales (S.D.D., "Shales Dolomitiques de Base") also called S.D.1a; (2) an overlying coarse-grained impure dolostone (B.O.M.Z., "Black Ore Mineralized Zone") also called S.D.1b) which is sometimes missing in the succession (e.g., in the Kambowé area). A generally barren reef-type stromatolite dolomite (S.R.C., "Roches Siliceues Calcaires") occurs between the two orebodies. Ores are known on 0.4-10 m thickness along the contact between this reef dolomite and both lower and upper rocks. The chalrite-silicate-dolomitic lenses or layers locally interbedded within the R.S.C. are also mineralised (e.g., Kamoto). In some deposits (e.g., Kambowé-Ouest), the primary stratiform mineralisation extends to the overlying carbonaceous detrital muds 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.D units (Calleux, 1983).

The Congo-type mineralised succession is very regular along strike (Fig. 2), showing the same lithological succession for >350 km, from Kowari (Demaison et al., 1963; François, 1973; Katoksha, 1975), to Tenke-Fungurume (Oosterbosch, 1950, 1951), Kambowé-Kazanga (Calleux, 1978a, 1983); Kavolua (Lefèvre, 1978a, b), Etoile (Lefèvre and Calleux, 1975) and Lubembe (Lefèvre and Tshianuka, 1996; Tshianuka et al., 1995). However, there is a clear across-strike lithofacies variation marking a progressive evolution from more near-shore (north) to more reeval (south) environments (François, 1973, 1974; Lefèvre, 1979; Calleux, 1978, 1983, 1994). This palaeoenvironmental variation seems to correlate with different copper-coal grades in the rocks (François, 1973, 1974, and details below). The northern (present coordinates) near-shore sequences ("Long" and "Kamwembe" facies) are characterized by the absence of stromatolites, the occurrence of dolomites and arenites in the Dolomite Shales Formation and of arenites in the Kambowé Formation. In these two sequences, the lithostratigraphic units usually hosting the orebodies are barren or poorly mineralised (e.g., Diéga Syndic between Tenke and Fungurume), except in the Tenke deposit. The Kamwembe facies occurs only in the Kowari area and represents a transitional facies between Long and Musotol facies. The southern sequences ("Musont" and "Kamwé" facies) are marked by: (a) reefs of stromatolites; (b) stromatolites in R.S.C.; (c) lack of arenites in Dolomite Shales and Kambowé Formations. There are no dolomites in the Kamwé facies Dolomite Shales Formation (e.g., Kambowé-Nord). This sequence hosts the most important copper-coal deposits (e.g., Kamoto, Fungurume), with only a few barren or poorly mineralised zones. The southernmost reef sequence ("Mendi" and "Luhia" facies) is marked by algal bioherms in R.S.C. and in the Kambowé Formation. The lithostratigraphic units usually hosting the orebodies are barren or poorly to well mineralised (e.g., Kambowé-Ouest, Luhiha, Luhiha).
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 (Durnley, 1960; Mendelssohn, 1961; Garlick, 1961b; Garlick and Fleischer, 1972; Van Eden and Binda, 1972; Calleux, 1973; Annes, 1974; Binda and Mulgrew, 1974; Clemney, 1974; Van Eden, 1974; Calleux and Lefevre, 1975). The Ore Shale Formation is a sedimentary unit ranging in lithology from quartzite-feldspathic wacke (Mufufira) to silstone (e.g. Konkol, Chambishi), to finely laminated argillite (e.g. Nkana) and to shaley or siliceous dolomite (e.g. Baluba, Mulhash South) (Binda and Mulgrew, 1974; Binda, 1994). The Musoshi Subgroup includes also lithologies (e.g. Nchanga, Nkana, Mufufira, Baluba, Mindola) transitional to those of the Congo-type lower and upper orebodies (Calleux 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, Kitwe/NW and Kitwe/SE sides of the Chambishi-Nkana basin, Luanshya, Malan, 1964; Clemney, 1974). The Ore Shale Formation is marked by evaporitic conditions, as shown by preserved blebs and beds of anhydrite (Brandt et al., 1961; Antola, 1974; Clemney, 1974), and by tidal flat/subtidal regressive and transgressive sequences grading into stromatolitic carbonates (e.g. Kitwe; Clemney, 1974).

The Ore Shale includes one (e.g. Musoshi-Konkol, Nkana; Jordan, 1961; Schmallhus, 1961; Calleux, 1973) or several orebodies separated by barren (<1 wt.% Cu) or low grade (1-1.5 wt.% Cu) mineralized beds (e.g. Nchanga and Nchanga-West orebodies). Lower and Upper orebodies at Luanshya: A, B, C Orebodies at Mufufira and Mimbula; Brandt et al., 1961; McKinon and Smit, 1961; Mendelssohn, 1961b; 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. Sulfides 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; Annes, 1974). Clemney (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 deduced 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 Felispathic Quartzite (T.F.Q.) at Nchanga and the weakly mineralised Glassy Quartzite at Mufufira (Binda and Mulgrew, 1974). These may be potential Zambian correlates of the third orebody hosted in the Kambwe Formation in the Congo-type deposits.
3.3. Mwasha Subgroup deposits

The Mwasha Subgroup is exposed for several hundred kilometres along major Luflian 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 Mwasha: e.g. Shituru and Mulunwishi-Kamindo (Likasi district), Kipol (Lukushi district), Kifumashi and Kasonta (Lubumbashi area) (François, 1974; Géomines, 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 Mwasha. 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 (≥0.5 wt.% Cu and up to 2% 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 orebodies host dolomitic limestones and dolomitic shales, lithologically similar to R.S.F/D stratiform and S.D.-type rocks of the Mines Subgroup, and interleaved 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 Mwasha and this copper mineralization (Lefebvre, 1974).

4. Copper-coalt distribution in the central Africa Copperbelt

Based on present day mined out production, ore reserves and resource evaluation using cut off grades of ×1.1 wt.% Cu, the economic orebodies host 32.2 Mt copper and 14.4 Mt cobalt in Zambia-type deposits, against 58.3 Mt copper and 46.4 Mt cobalt in Congo-type deposits. This adds up to ~140 Mt copper and 6 Mt cobalt for the whole central African Copperbelt (Fremantle, 1988a; François; Géomines, unpublished data). Therefore, the Zambia-type orebodies contain >=7% of the copper whereas the Congo-type orebodies host >=7% 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 1.15 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 (Kamwazu et al., unpublished work) indicate that the total amount of copper and cobalt contained in the Katangan economic orebodies represents ±8% and ±8%, respectively, of the total (i.e. 1850 Mt copper and 750 Mt cobalt, respectively) metal contained in the Rono sedimentary rocks.

The distribution of copper and cobalt deposits is related to the regional tectonic control of the distribution of the
Mines Subgroup and lateral correlate units along the Luflian Arc (François and Oosterbosch, 1968; François, 1973, 1974). The Long and Kitumusambu facies exposed between Kaboso and Tonke contain 50% and 10% 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 Kalambwe facies exposed between Kolwezi and Kakabali–Pungurume host copper-rich (>2.0 wt% Cu) and cobalt-poor to cobalt-rich (<0.1–0.5 wt% Co) ores, representing 50% 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 Kabangwe to Etoile and host copper-rich and cobalt-rich (>2.0 wt% Cu and 0.4–0.6 wt% Co) ores. Substantial nickel (from several hundred ppm to 0.2 wt% Ni) is associated with cobalt in the Menda and Luishia facies, forming Ni-Co sulphide deposits (e.g. Sintolobwe). Between Lupto and Lubambe, the Luishia facies host cobalt-poor (<0.1–0.4 wt% Co) orebodies.

In Zambia, cobaltiferous ore deposits occur south of the Kafue Anticline (Fig. 2), e.g. Konkola-Chililabombwe, Nchanga, Chambishi Southeast, Chibuluma (West of Nkana), Luanshya and Buloba deposits (Amois et al., 1983; Amdis and Simmonds, 1984; Freeman, 1988b). Cobalt contents are generally between 0.1–6.2 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 Katate Anticline, e.g. Kinshasa (Congo), Mushila, Rwana Mhubea (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 (0.02–0.02). This group includes most Zambia-type copper deposits and a few Congolese deposits (e.g. Matshari in the Kolwezi area, Kakanda-Nord, Kalengya in western Zambia); (2) the second group represents cobalt-rich copper deposits marked by high Co/Cu ratio (0.02–2.0), including most Congolese deposits and some deposits in Zambia (e.g. Nkana-Mindola, Nchanga, Baluba). The highest Co grades within the total resources in Zambia (Co/Cu = 0.10–0.5) occur in the Buluba, Nkana-Mindola, Chibuluma deposits (Freeman, 1988b), which show transitional lithotrites between Zambia-type and Congolese-type mineralized units. Local high grades are documented in the Nchanga deposit. The Mwalesha Subgroup Shitantu 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–borite at the bottom, followed by bornite–chalcopyrite and chalcopyrite–borite–dominant zones, and pyrite at the top (e.g. Chambishi, Chibuluma, Baluba, Nchanga, Musashi, Garlick, 1961c; Lee-Potter, 1961; McKinnon and Snaith, 1961; Calixte, 1973, 1974). A similar trend marks some Congolese-type deposits. For example, the Kaboto deposit is characterized by chalcocite–digenite–borite 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; Dijkstra, 1962, 1963, 1969). Outside the orebodies, pyrite is common and coexists sometimes with a few chalcopyrite grains.
Etoile and Kambwe-Ouest deposits (Congo) display a different sulphide zonation in the same lithostratigraphic units. At Etoile, two sequences from chalcolite to bornite and chalcocyprite were observed, one from grey R.A.T. to D.Strat., the other from R.S.F. to S.D.B. (Lebfevre and Calleux, 1975). At Kambwe-Ouest (Calleux, 1983, 1986), chalcopyrite is dominant at the base (Grey R.A.T.) and at the top of S.D.B., whereas a chalcedon-bowenite-borneite 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” (Kambwe Formation) is hosted in dolomitic shales and dolomitic limestones at Kambwe-Ouest, with a remarkable facies of metravertical zoning marked by the occurrence of pyrite-chalcopyrite-bornite-chalcopyrite-pyrite ores (Fig. 8). Carrolite (cobalt–copper sulphide) is irregularly distributed in the orebodies. It is associated with chalcopyrite and pyrite in copper-poor zones (e.g., Kambwe-Ouest, Chibuluma, Nkanokia in the Kambwe-Ouest deposit, a 0.5-1.5 m thick carrolite-chalcopyrite orebody frequently occurs in the pyritic Grey R.A.T. below the base of the orebody. Centimetric grains of carrolite occur in the poorly mineralised R.S.F. and dolomite orebodies in talcose dolomites of the Kambwe Formation (Figs. 4, 5).

The lower orebody sulphide mineralisation in the Lower Mwashya Shiura deposit includes disseminated pyrite, chalcopyrite, bornite, minor carrolite/chalcopyrite and supergene copper sulphate (argenteous, chalcocite) associations, similar to those of the Mines Subgroup orebodies (Lebfevre, 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 Cu/Co 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, linnite and carrolite occur in the Ore Shale, mainly within its lower part (e.g., N'Ganga, Chambishi, Mindola, Nkana, Chibuluma, Mulushi, Baluba, Mendesboma, 1986; Annels et al., 1983; Annels and Simmonds, 1984; Fig. 9d).

Cobalt in cobalt-rich disseminated sulphides at copper-rich stratiform ores from both Congo- and Zambia-type deposits include mostly chalcopyrite and cobaltite at Kinshasa and Luiswishi (Mondur, 1983; Ngoyi and Mondur, 1987; Loris et al., 1997), siegenite at Kambwe-Ouest and Luiswishi (Calleux, 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-cuellite, Co-vaseline and siegenite in Shinkolobwe and Swansea (Derricks and Vans, 1956; Derricks and Oosterbosch, 1958; Oosterbosch, 1963), siegentie and violatite in Kamituba (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 carrolite and catinite, chalcostite, chalcocite and Co-pyrite from Kabon, Kambwe-Ouest, Shinkolobwe, Moshio-Kantoka, Baluba, Chibuluma, Chambishi (Bartholomé et al., 1971; Calleux, 1974, 1977; Craig and Vaughan, 1979; Annels et al., 1983; Sweeney et al., 1986). Sulphides from zone deposits (e.g., Kamituba-Sud II in the Kambwe area) contain several hundred to 1000 ppm Ni in the oxide ores, but Ni/Co ratios remain very low (≤0.01). Microprobe analyses identified a complete solid solution between pyrite (FeS2), catinite (CoSx) and vaeite (NiSx) (Loris, 1998; Loris et al., 2002). Sulphides of the linnite group were also documented, with chemical compositions indicating siegenite, linnite, carrolite or polyanite. In the richest cobalt deposits (e.g., Shinkolobwe, Swansea), Ni/Co ratios are higher (e.g., 1:4) since nickel concentration reaches 0.5 wt.% in a disseminated ore containing Ni-cuellite thiospindal, siegentie, vaeite in addition to pyrite and chalcopyrite (Derricks and Vans, 1956; Derricks and Oosterbosch, 1958). Linnite (CoSx)-carrolite (Co3CuS4) thiospindal solid solutions contain significant amounts of Ni and Fe. Zambezi thiospindals yielded 0.45-2.53 wt.% Ni (Annels et al., 1983), whereas higher values (11.9-12.2 wt.% Ni) were reported at Shinkolobwe (Craig and Vaughan, 1979). These data indicate...
that nickel is closely linked to primary Cu–Co ore in the central African Copperbelt.

Since 1933, gold, platinum-palladium and silver were mined from Congo-type Cu–Co stratiform deposits, i.e., Mutoshi (formerly Ruwe), Mwenda (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 (d’Hendriques, 1956; Jedwab, 1977). 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 hydrides), As/Se/Te metallic compounds (e.g., coberoschite, moncheite, troglaitie) or sulphides (e.g., innesite, Se–As sulphides). Sub-economic occurrences were recorded in oxidized from a few Cu–Co deposits, e.g., gold at Kalongwe, Fungurume, Kamoya (Kambove area), Lilensi (d’Hendriques, 1956), Pd–Au at Mindigi (Jedwab, 1977). The grades in these occurrences may reach >0.2 g/t Au, >2.9 g/t Ag and >0.5 0.4 g/t Pt Pd. Platinum and palladium are generally hosted in argentiferous. 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-type deposits, e.g., at Kamoto-Principal (Bartholomé, 1962, 1963; Bartholomé et al., 1971, 1972; Dmanche, 1974). Musoshi
Framboidal pyrite (pyrite I) grains (Fig. 10a) occur mainly within zones adjacent to the oreebodies (below, above, and laterally). Sometimes, chalcopyrite (-I) or bornite (-I) form the core of this early pyrite (Cailleux, 1974). Micromobre analysis indicated the presence of copper in framboidal pyrite-I and revealed cobalt-nickel rich pyrite (-I) forming the outer rims of pyrite-I grains, e.g. at Kamoto (Bartholomé et al., 1971), Musoshi (Cailleux, 1974) and Kinshasa (Ngozi and De Jonghe, 1997). Parageneses with pyrite-I (-Co,Ni) pyrite-II (bravais) -pyrite-III parageneses were reported in the Lualaba 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 (Cailleux, 1983).

Primary chalcopyrite (-I) and bornite (-II) are the main copper sulphides in the orebodies (e.g. Kambove-Ouest); they grow at the same time as separate or coalescent grains. Carrolite and pyrite-III coexist with copper sulphides-II (mainly chalcopyrite). Chalcopyrite-II includes framboidal pyrite-I, e.g. at Kinshasa (Ngozi and De Jonghe, 1997). Bornite-II replaces pyrite-I (-II), e.g. at Kamoto (Bartholomé et al., 1972), as shown by carrolite grains including well-preserved aligned pyrite-I, whereas pyrite grains outside carrolite have been completely replaced by bornite-II (Fig. 11). The textural relations indicate that bornite-II grew after the development of carrolite grains. In the Lualaba deposit (Loris, 1996; Loris et al., 2002) copper sulphides-II and sulphides of the laurite group (laurite -digenite-carrolite/polydymite) formed after those of the pyrite group (pyrite-utahite-vacancy).

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

Borinite (-II) grains include digenite in boronite-dominant baid (Cailleux, 1986). In these boids, carrolite grains include borinite II in the centre and digenite-II towards the rim. This indicates that carrolite grew before and alter the conversion of borinite into digenite.

Replacement carrolite forms the external rim of chalcopyrite and/or bornite (-II or -III) grains (Fig. 12). The transition between carrolite rims and chalcopyrite or bornite cores is marked by a digenite fringe (Fig. 12a, b) and small pyrite grains occur within the carrolite rims (Fig. 12c). Pyrite (III, IV), chalcopyrite and bornite (-IV) overgrow these parageneses (Fig. 12d). Some carrolite grains include copper sulphides showing replacement textures by carrolite; others show microfactions filled by chalcopyrite or bornite (-IV). In Kambove-type deposits (e.g. Musoshi), bornite frequently includes chalcopyrite both as lattice or irregular exsolutions (Cailleux, 1973, 1974). Similar parageneses occur in the Shimuru lower orebody, forming also several generations of sulphides (Lefebvre, 1974).
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, borite and chalcopyrite (Amels, 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 (Rothdassell et al., 1975; Amels, 1974; Katesheba, 1975; Calieux, 1978a, b). These nodules were completely replaced by dolomite, quartz, pyrite and 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 Masoshi (Zambia-type) deposit (Caltex, 1973; Calieux and Dimanche, 1973), the barren rocks below and above the orebodies are marked by detrital ilmenite (IL) showing partial to complete conversion into leucoxene (Li), with intermediate products (IL + Li or Ri + Li). These minerals are associated with diagenetic haematite. In the Minesi orebodies, the conversion of ilmenite into Li-Rt is complete, and 65% of the leucoxene-rutile grains show associations and intergrowths with pyrite-L, -Rt and/or copper sulphides-III, whereas 25% of the leucoxene-rutile and 10% of the sulphides occur in isolated grains (Caltex 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-Kirme (Caltex and Lefebvre, 1975), Etiole (Lefebvre and Calieux, 1975) and Kambove-Ouest (Caltex, 1978a, b). In the S.D.S., this association consists of frambooidal pyrite Li.
In the Kambwe Formation, carnallite is the major sulphide in tuff-dolomite bearing beds and layers (Figs. 4 and 5), whereas dolomite-quartz bearing beds host mainly copper sulphides (Caliebe, 1983). Talc in these rocks is diagenetic and presumably results from an early saprolite that consisted of calcite (converted into diagenetic dolomite) instead of growing from the reaction between dolomite and quartz (Bartholomé, 1966; Caliebe, 1979). However, a metamorphic origin for the 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. Derricks and Vaes, 1956; Derricks and Oosterbosch, 1955; Mendelssohn, 1961b; Demesmaeker et al., 1963), related to the first Lufilian compressional deformation event known as the Kolwezian tectonic event (Kampunzu and Caliebe, 1999 and references therein). The heterogeneous distribution of strain during this event with the maximum strain focused along thrust sense shear zones, possibly controlled by evaporitic layers (Caliebe, 1994; Caliebe 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. Niara, Lunshya, Mufila; Mendelssohn, 1961k; 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-tectonic veins both in Zambia and Congo (e.g. Garlick, 1961b; 1964; Mendelssohn, 1961c; Caliebe, 1983, 1997; Sweeney, 1987; Caliebe and Kampunzu, 1995; Loris, 1996). In the orebodies, minor remobilization of stratiform ores is shown by a few cross-cutting mineralized 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 ~0.01 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 δ^{18}O and δ^{13}C values for Footwall and Ore Shale dolomites in Zambia define two fields in Fig. 14 (Sweeney et al., 1986). δ^{18}O values for Footwall dolomites are between +20.82 and +26.38, SMOW. The Konkola Ore Shale carbonates pseudomorph after anhydrite nodules or lenticles yielded δ^{18}O values between +14.56 and +16.15, SMOW. For comparison, δ^{18}O present-day mine waters from the

![Fig. 14. Values of δ^{18}O plotted against δ^{13}C for carbonates from Zambian Footwall and Ore Shale rocks (Sweeney et al., 1986).](image1)

Copperbelt yields of ~6.2%, SMOW (Sweeney et al., 1986).

 Sulphur isotopic data on sulphides from Cu-Cu mineralization in Congo and Zambia are dispersed (Fig. 15). However, they show a consistent large range of δ^{34}S values (Jensen and Decho, 1962; Decho and Jensen, 1965; Sweeney et al., 1986; Okitauchi, 1989; Hoy and Okamoto, 1989; McGowan et al., 2003; Lerouge et al., 2004), from high negative to high positive values, which characterize the sediment-hosted deposits (e.g. Okamoto and Rye, 1979; Krouse, 1980; Misi et al., 2000; McGowan et al., 2003).

![Fig. 15. Sulphur isotope values for sulphides and sulphates from Congotype deposits (Kamoto, Kambove-Kotex, Luvungi, Etoile, Bumbu; data from Okitauchi, 1989; and Lerouge et al., 2004), sulphides from the Zambian Ore Shale, Footwall and veins at Konkola, and sulphates from Mufila ore horizons (data from Sweeney et al., 1986). CP = chalcopyrite, CR = carnallite.](image2)
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 ($<50^\circ$C). However, for deposit 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 $\sim +2\%_o$. The same hypothesis is also proposed for the Mesozoic and Neoproterozoic lead-zinc deposits of the São Francisco Craton (Misi et al., 2000). Rare $\delta^{34}$S sulphate analyses from fossil rocks are $\sim +17\%_o$ at Mulilansolo in Zambia (Sweeney et al., 1986) and $+22.6\%_o$ in the Mines Subgroup (average) at Kolwezi (Bada et al., 1989). These values are 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 Kolwezi (Fig. 16a; Sweeney et al., 1986) and Luwirikian 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 (higher negative values down to $\sim -70\%_o$) during transgressive events, whereas they become heavier (higher positive values up to $+70\%_o$) 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-enrichment in a marine reservoir during a regressive period, marking a basin closed from the seawater. The decrease of $\delta^{34}$S values, down to $\sim -15\%_o$, 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

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**Fig. 16.** Sulfur isotope composition of sulphides along vertical sections through (a) the Zambia Ore Shale (Sweeney and Bindl, 1988a), and (b) the Congo-type ophiolites in the Luwirikian deposit (Lerouge et al., 2004), showing transgressive-regressive events as those indicated by the host-rock lithologies (Sweeney and Bindl, 1988a, b; Calmeau, 1994).
regime was persistent during the deposition of the sedimentary hosting the Lower and Upper orebodies (Kamoto and Dolomite Shales Formations). These results are in agreement with the interfacial transition transgressive-regressive evolution of the pre-depositional sediment from the Mine Subgroup in Congo (Bartholomé et al., 1972; Calvet, 1983, 1994) and the Ore Shale Formation in Zambia (Swann et al., 1986).

The sulphur isotopic data of coexisting sulphide pairs at Kondola (Sweeney et al., 1986) and Luwirv (Lerouge et al., 2004) show heterogeneous isotopic fractions between the sulphides, indicating crystallization at disequilibrium in the Luwirv deposit. Sulphides-carbonate sulphur 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 (chloropyrite, marcasite, arsenopyrite) 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 neoformation of sulphides in veins during the Luflian tectono-metamorphic events. The preservation of disequilibrium between coexisting sulphides in veins suggests that the reworking was not strong enough to re-equilibrate the $\delta^{34}S/S^{33}S$ ratios.

8. Thermometry

Fournier (1975, 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 30 °C/km which is a maximum value calculated by Chazel (1986) in rocks from Luflia, the temperature at the 6-km burial depth should be between ~60 and 300 °C. The regional metamorphism related to the Luflian 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. Meckleston, 1961b; Oweis and Close, 1962; Drysdall et al., 1972; François and Calvet, 1981; Tembo, 1994). Most of the Zambian-type deposits in Zambia (e.g. Nhanga, Chambishi, Mulashi, Mufulira, Nkana, Luanshya) and some deposits in Congo (e.g. Muoschi, Kamono) evolved under the greenschist facies, possibly around ~250-400 °C (Richards et al., 1988). Particularly at Muoschi, late quartz + biotite + muscovite + carbonates + sulphides ± anhydrite ± barite related to the Luflian orogeny record temperatures around 400 °C (fluid inclusion data in quartz; Richards et al., 1988). In northwestern Zambia (Domes area), peak metamorphic conditions at F1 (Di Kolvazzat phase of Kambu and Calvet, 1999) are around 550 °C and 15 kbars, followed by a decompression at 9 kbars (Loi et al., 1992; Steyer and Andersen, 2003).

9. Fluid inclusions

Fluid inclusions found in gangue minerals (Ademosite, micasite and quartz) from Congole-type Kamoto-Principal, Shinkokwe, Kambove-Ouest and Luwirv orebodies (Pirimolin, 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 100 °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 temperatures of ~200 °C and salinities estimated around 40 wt.%.

Audouin (1982) and Audouin et al. (1984), working on fluid inclusions contained in dolomite veins of the R.A.T. formations and on identical inclusions associated with the hematite-magnetite 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$_2$, CaCO$_3$). The NaCl and KCl concentrations in these inclusions are relatively low, which is consistent with the R.A.T. composition (Kambu and Calvet, 1999).

In Zambia, Sweeney (1987) found that (1) fluid inclusions in quartz veins cross-cutting the Ore Shale at Kondola 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-depositional tectono-thermal event and formed by lateral secretion of fluids during late diageneric de-watering at temperatures of ~120 °C.

Fluid inclusions in quartz from quartz-hematite veins cutting the Footwall at Muoschi (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 Luflian orogeny.

Fluid inclusions from early quartz associated with pyrite and marcasite (pseudomorphs after pyrrhotite) in the Chambishi orebody yielded salinities in the range of 9-16 wt.%, whereas fluid inclusions from syn-metamorphic veins yielded higher salinities between 16 and 22 wt.% (Annela, 1989).

Recent studies by Greyling et al. (2002) on various tectonic settings (pre-deformation, syn-tectonic, post-deformational) showed the following scenario: (1) There
are primary and secondary inclusions of \( \text{H}_2\text{O}-\text{NaCl}-\text{CO}_2 \pm \text{CH}_4 \) 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-phyllitic assemblage veins cross-cutting the orobridges in the Nkana synclinorium, and representative of post-tectonic fluids, contain \( \text{H}_2\text{O}-\text{NaCl} \) 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 (100–130 °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 silt fractures and deriving metals from deep-seated mafic rocks, as proposed by Annds (1974, 1979, 1983), Annels and Simpson (1984) and Leebre (1989). Indeed, fracture-filling ores expected to mark unreeling 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; Sebagezzi, 1993, 1997a,b; Geommines, unpublished aeromagnetic data).

Similarly, there are no data to support the hypothesis of Unger (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 Nguva Group sediments; (2) convective circulation of basinal ore solutions driven by a thermal gradient and with leaching of metals from Nguva plutons, 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 Nguva 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 Charttrand, 1986; Haynes, 1986; Rose, 1989; Walker, 1998) 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 metal 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 10⁸ m³ of source rocks, which is about 100 times the volume of footwall sedimentary rocks in the Luflian 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 orobridges; 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 baring 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 Luflian compressional structures such as thrusts related to the Kolwenzian tectonic event (Kampunzu and Calteux, 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 Luflian tectonic–metamorphic events.

The most important among these features are the following: (1) one set of low-salinity fluid inclusions yield equilibration temperatures >200 °C, contrasting with lower temperatures (<100 °C) obtained on high-salinity inclusions preserving primary features (Pinnolino, 1970; Andeoud, 1982, Andeoud et al., 1984; Sweeney, 1987; Richards et al., 1988; Annds, 1989; Greyling et al. 2002); (2) local syn-kinematic hydrothermal leaching (Ngongo, 1975a; Leebre, 1976b; Calteux and Kampunzu, 1995; Calteux, 1997) indicate small scale metamorphic remobilisation of hypogene fluids (cf. fluid inclusion composition) inducing recrystallisation of both gangue and ore minerals and local development of barren and mineralised veins; (3) kyanite-serpentinite-florentite and paragonite-plagioclase assemblages in veins indicate temperatures up to 400 °C in the presence of hypersaline fluids (Lefebvre and Patterson, 1982; Guezel, 1996). The genetic model
developed below puts emphasis on the mineralising processes that were the most important in the formation of the primary orobodies.

The Mina/Musindi orobodies are lithologically and 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 sulphides in Congo-type orobodies (Guy R.A.T.-Dkat-a-R.S.F.-S.D.B.-Kambore 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 orobodies) 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 orobodies. This transitional lithology indicates the existence of reducing/oxidizing from (Caillieux, 1978a, 1994). A thinner but similar transition zone occurs over tens of centimetres between the Zambian Ore Shale and its footwall (e.g. Musola, Caillieux, 1977).

The earliest sulphides (pyrite-I, Co-Ni-pyrite-II, chalcopyrite, bornite-I) were deposited before the lithification of the host rocks, i.e. they are syngenetic to early diagenetic. The interpretation is based on the assumption 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 sulphides (Anands, 1974; Sweezy et al., 1987). Inclusions of copper sulphides-I in frambooidal pyrite indicate that the earliest Cu-sulphides precipitated early, and some frambooidal pyrite and thus represent also syngenetic minerals. The increase of Cu-Co-Ni content from the core (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 contents in host rock primary minerals such as dolomite (Sweeney and Binda, 1989a,b; Lorís, 1996) indicates that the transition elements were readily mobilized and even concentrated in the depositing water during sediment deposition.

Pyrite group sulphides (pyrite, catticite, vaseline) were deposited before Co-Cu sulphides-II. According to Craig and Vaughan (1979), the pyrite group forms a crystallisation sequence pyrite-Co-Co-Cu-Antimonite-vaseline (e.g. at Luvisi), marking Fe-Co-Ni compositional changes of the forming fluids.

The second generation of sulphides (Co-Cu sulphides-II) replaces or includes sulphides of the first generation (i.e. bornite replacing pyrite, chalcopyrite including frambooidal pyrite). Intergrowth of Cu-Co sulphides-II with syngenetic 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 orobodies.

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 sulphides led to the growth of bornite at their rims. The reactions involved are as follows (Caillieux, 1985, 1986):

\[ 2CuFeS_2 + 2Co^{2+} \rightarrow CuSCoS_2 + Cu^+ + 2Fe^{2+} \]
\[ 3CuFeS_2 + 6Co^{2+} \rightarrow 3CuSCoS_2 + 2CoS + 3Fe^{2+} \]

The reaction released during these reactions enhanced at the contact with carrollite, the conversion of chalcopyrite or 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 hangwall of the Congo-type orobodies indicate that the brines was still enriched in cobalt after the deposition of Co-sulphides in the orobodies.

Sulphur isotopic data on nodular and lenticular anhydrite from the orobodies and barren rocks from the same unit indicate that anhydrite 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 107 °C) by bacterial reduction of sulphate ions in the brines and possibly by reaction with earlier anhydrite (Anands, 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 (Hy and Omoto, 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 (Caillieux and Kampunzu, 1995; Kampunzu and Caillieux, 1999). Fluid inclusion data reviewed above (e.g. Grewling 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 (Anands, 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 (Caillieux and Kampunzu, 1995; Caillieux, 1997; Kampunzu and Caillieux, 1999).

Brine oversaturation in metals resulting in the deposition of the syngenetic to early diagenetic sulphides was controlled by evaporation, probably within sabkha basins (Caillieux, 1986; Cullick, 1989). Changes in Eh-pH conditions may explain the consistent sulphide zonation in the Copperbelt orobodies (Caillieux, 1986).
The model of primary concentration of copper in the Copperbelt stratiform orebodies involves the mixing of oxidised mineralising brines from the hypersaline lagoon with meteoric fluids rising in organic deposits. This model is supported by: (1) the occurrence of relict evaporite 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 progressive sub-aqueous lagoon, the first generating the lower and upper orebodies and the second forming the third, minor orebody; (2) the strong lithostatigraphic 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 metasomatic processes.

Orebodies or sub-economic Cu sulphide ores are hosted in footwall sedimentary rocks deposited under oxidised conditions in the Zambia-type siliciclastic Mutombo Formation (e.g. Mulushi Knoll in the Lusashi district, Chingola; Binda, 1997). They are Buccaneer bodies located at different stratigraphic levels within the Mutombo unit (Fig. 6). Van Eden and Binda (1972) and Binda (1987) suggest a downward migration of mineralising diagenetic brines remobilising copper from the Ore Slate to the porous footwall formation. However, the occurrence of these peculiar orebodies of pyrite-I included in copper sulphides-II at Kinnen (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 Slate acted in the Mutombo 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 geophysical data indicate that the Archaean Zimbabwe craton and the Palaeoproterozoic basement complex in the Bangwulu 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 complexes, cobalt in Nkatuma, copper 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 (Coraz, 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 ironstones in the Mwamba tuffs (Rainaud et al., 1999, 2003).

In the case of the Lower Mwasha orebodies at Shituru, the Cu-(Co) mineralisation 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 transformation of local sedimentary material.

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. classic vs. carbonate host rocks), they display a large number of analogies, including: (1) their location in laterally correlating lithostratigraphic units deposited in supratidal to sabkha-type highly saline environments; (2) similarities of ore textures 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 meta-sulfidic 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 correlatives 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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