Sediment-hosted Zn-Pb-Cu deposits in the Central African Copperbelt

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ABSTRACT

Sediment-hosted epigenetic sulphide Zn-Pb-Cu ore deposits in the Central African Copperbelt in the Democratic Republic of Congo and Zambia are mostly hosted in deformed shallow-marine platform carbonates and associated sedimentary rocks of the Neoproterozoic Katanga Supergroup. Economic orebodies, that also contain variable amounts of silver (Ag), Cu, Co, Ga, In, Mo, Ni, and V, occur mainly as irregular pipe-like bodies associated with collapse breccias and faults as well as lenticular bodies subparallel to bedding. Kipushi and Kolwezi in the Democratic Republic of Congo and Zambia, respectively, are the major examples of carbonate-hosted Zn-Pb-Cu mined deposits with important byproducts of Ge, Ga, Ag, and V in the Lufillian Arc, a major metallogenic province famous for its world-class sediment-hosted stratiform Cu-Co deposits. The carbonate-hosted deposits range in age from Neoproterozoic to early Palaeozoic (600 to 450 Ma). The formation of the relatively older Neoproterozoic deposits is probably related to early collision events during the Lufillian Orogeny, whereas the younger Palaeozoic deposits may be related to post-collisional processes of ore formation. Fluid inclusion and stable isotope data indicate that hydrothermal metal-bearing fluids evolved from formation brines during basin evolution and later tectogenesis. Ore fluid migration occurred mainly along major thrust zones and other structural discontinuities such as kants, breccias and faults within the Katangan cover rocks, resulting in ore deposition within favourable structures and reactive carbonates of the Katangan Supergroup.

Keywords:
Zn-Pb-Cu deposits
Sediment-hosted deposits
Central African Copperbelt

1. Introduction

The arcuate shaped Lufillian Arc is part of the Neoproterozoic system of Pan-African orogenic belts with two N-S trending orogens on the eastern (the Mozambique Belt) and western margins (West Congo, Kalahari and Saldanha Belts) of southern Africa, linked by a third N-S trending Damara Belt (Fig. 1). The transcurrent Mwembeshi Dislocation Zone (Fig. 1) separates the Lufillian Arc from the Zambesi Belt (Urug, 1987). Geophysical data (Eberle et al., 1995, 1996; Cotta, 2000) indicates that the Lufillian Arc is probably linked to the NE-trending Damara Belt, but its link with other Pan-African orogens in the west is obscured by Phanerozoic cover. The evolution of these Neoproterozoic orogens and the mostly undeformed supracrustal sequences in the associated Neoproterozoic to lower Palaeozoic basins (Fig. 1) spans over a period of 500 million years, starting within the plate margin, and culminating with collisional nappes from ca. 1000 to 700 Ma, and culminating with collisional nappes from 970 to 450 Ma (Kanpunu et al.)

A number of epigenetic Zn-Pb-Cu massive sulphide deposits, including the major deposits of Kipushi and Kolwezi, are hosted in deformed platform carbonates of the Lufillian Arc. Most of these deposits are relatively small, typically with only a few thousand tons of ore, including Kasevang and Lumbe in the Democratic Republic of Congo (DRC; hereafter Congo) and also Bob-Zinc, Lubumbashi, Millberg, Monakushi, Shamboro, and Star Zinc in Zambia (Fig. 2). As a consequence, these minor deposits and prospects have only been exploited at a small scale if at all. However, the Kipushi and Kolwezi deposits are exceptionally large, with millions of tons of predominantly massive sulphides contained within stratigraphically extensive pipe-like bodies surrounded by oxidised diorite.

These carbonate-hosted deposits are of special interest since they are polymetallic (Zn-Pb-Cu-V-Co-Ag), and also contain minor amounts of molybdenum, copper, and tungsten. In addition, they are closely associated with the world-class stratiform Cu-Co mineralization of the Central African Copperbelt. However, although detailed descriptions of the individual deposits have been made in the past and a significant amount of data documenting the various attributes of these deposits has been collected in the last decade, the regional occurrence and mineralisation processes related to the genesis of these deposits have not yet been described holistically and, furthermore, their relationship...
to the stratiform Cu–Co deposits is still poorly understood. It is therefore the aim of this paper to synthesize and critically assess the available geological data and evidence related to the occurrence and genesis of carbonate-hosted Zn–Pb–Cu deposits in the Lufilian Arc of Central Africa in order to better constrain the processes of mineralization.

7 Geological background

The Lufilian Arc (Fig. 1) of the Central African Copperbelt is a northward-convex Pan-African orogenic belt consisting of Neoproterozoic metamorphic rocks of the Katanga Supergroup (Mokola cache, 1040 Ma; Binda and Mulenga, 1974; Unger, 1982; Chalmers et al., 1994, 1995). Basement rocks underlying the Katanga Supergroup include Neoarchean granites and gneisses of the Congo Craton in the western part of the Lufilian Arc (Ry et al., 2001) and Palaeoproterozoic schists, granites and gneisses of the Bambute Region (Ry et al., 2001; John et al., 2006a). The external fold and thrust belt of the Lufilian Musozoic Complex (LMC) on the Copperbelt (Mickel-Smith, 1981b; Ngeli et al., 1991; Banaud et al., 2005a) and the quartzite–metapelitic succession of the Mina/Kibaran Supergroup (Garlick, 1981; DeWaer et al., 2006; Kokonyangi et al., 2006).

According to Roy et al. (1991), the Neoarchean Congo Craton (2533–2538 Ma) was affected by a 2560 Ma tectono-thermal event, when migmatites and associated granites were generated. Banaud et al. (2005a) have interpreted the Palaeoproterozoic (2073–1874 Ma) LMC as a regionally extensive magmatic arc tectonics which collided with the Tanzanian crust during the ca. 1860–1830 Ma Ufandikanye orogeny. The Mina/Kibaran Supergroup was deposited between ca. 1650 and 1550 Ma (DeWaer et al., 2005; Kokonyangi et al., 2006).
was involved in a full Wilcox cycle of rifting, ocean opening and closure, followed by subduction and collision [Kampuzza et al., 1986; Rummel, 1991; Kukunanga et al., 2000] which culminated in the assembly of the非洲 Orogeny (Dabie et al., 2000) during the Mesoproterozoic Inundation of the Congo (Ngezi and Pera, 2000). The formation was the youngest of the Katanga Group and the oldest of the Central African Copperbelt (Garlick and Brummer, 1951).

2.1. The Katanga Supergroup

The Katanga Supergroup is commonly divided into two lithostratigraphic groups (Table 1): the basal Rono, the middle Nguha (formerly lower Kafumbugo) and the upper Katanga (formerly upper Kafumbugo) at the top (France, 1973b, 1987, 1995; Calheux, 2003; Batiukin et al., 2007).

The Rono Group in Zambia consists of a basal siltstone unit (Misdola Subgroup), a middle carbonate and siliciclastic unit (Kwewo Subgroup) and an uppermost carbonate unit (Kabimhongwe Subgroup). According to detailed correlations of the Rono Group sedimentary rocks between Congo and Zambia performed by Calheux et al. (1994, 1996), these units corresponded to the D.R.T. (Dakar Arc Est) argilite of the Congo, respectively the Ngezi and Pera (2000) and Batiukin et al. (2007). The formation is marked by a general north to south decrease in thickness due to increasing carbonate deposition and decreasing grain size in siliciclastic rocks southward. Such trends suggest a proximal facies in
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*Fig. 92 and 93 are the codes for Rasa, Miocene, and Rendogongma Groups, respectively. 3L and 3R are codes for Lower Rasa and Upper Rasa, respectively, in Kangan.*
the north and a basin open to the south (François, 1987; Batulle, et al., 2007).

The uppermost Kudelitnga Group is subdivided into three subgroups (Kombe, Nigele and Bajo) in Congo (Batulle et al., 2007). The Kombe Subgroup consists mainly of shale, siltstone, and carbonates, and it is marked by the basal glaciogenic Pettit Conglomerate (Kaninde Formation) overlain by a carbonate (Kaninde Formation). The Nigele Subgroup is a sequence of pelites, siltstones and sandstones, whereas the Bajo Subgroup is an arenaceous unit of conglomerates, arkose, and sandstones.

2.2. Tectonic evolution of the Katanga Supergroup

Initial continental rifting and sedimentation began soon after 2.0 Ga. as described by Wegler (1989). The Kaime Formation, the eldest formation of the Katanga Supergroup, was deposited in a forearc basin environment characterized by extensional-related mafic plutonism and volcanism (Kamupuzu et al., 1991, 1993, 2000). The intracratonic rift developed in response to tectonic stress associated with the breakup of the Rodinia Supercontinent (Regen et al., 1995; Uming, 1996; Weil et al., 1997) due to upwelling of asthenospheric mantle that resulted in the generation of tholeiitic mafic magmas (Tondo et al., 1998). The late-rifting rifting stage evolved into the pre-oceanic rift stage from ca. 765 to 735 Ma (Kamupuzu, et al., 2003; Barron et al., 2003) when oceanic crust was formed from extension-related formation of tholeiitic mafic dikes and sills and intrusion of mafic to felsic lavas and tufts (Kamupuzu et al., 1991, 1993, 2000; Merett et al., 1997; John et al., 2001). This rifting phase is marked by the Mibeli Subgroup in the Eifel province (Kamupuzu et al., 1991, 1993, 2000; Merett et al., 1997; John et al., 2001). During a major phase of compressional tectonics and subsequent folding, the evolution of the continental rift to the pre-oceanic rift stage (Kamupuzu et al., 1991, 1993, 1996) the ocean basin widens to 1000 km (John et al., 2003) with the intracratonic units of the Mibeli Subgroup (Calvert et al., 2007) and of the overlain Nguba and Nkumbe Subgroup deposits.

Both the Grand Congolais and the Petit Congolais, which occur at the base of the Ntcha and Kudelitnga Supergroups (Table 1), are glaciogenic sediments which may be correlated to the global Suurini (ca. 710 Ma) and the McMinnon (ca. 635 Ma) glaciations, respectively (e.g., Hofman et al., 1998; Fanning and Link, 2004; Hoffmann et al., 2004). The duration of the last glaciometric event is punctuated by the 1.0-1.2 Ma age of the Nguba and Nkumbe Subgroup deposits.

The extension was followed by convergence of the Congo and Kalahari Cratons, leading to subduction of oceanic lithosphere and edifice formation at around 538 ±11 to 519 ± 10 Ma (Nd-Ne garnet-whole rock ages; John et al., 2003). Le Roux et al. (2004) have determined U-Th-Pb ages of 701 ± 49, 603 ± 31 and 508 ± 8 Ma on monazite and zircon fractions from the Lubumbashi-Cu-Co deposit in Congo which are within the error range of edifice formation at 518 and 606 Ma. The 701 Ma monazite age is in agreement with the 749 ± 6 Ma Nd-Ne garnet-whole rock age of Costier et al. (1992) for peak metamorphism in the Dombé Region. Plate convergence and subduction therefore probably occurred from ca. 750 to 600 Ma, during what is commonly referred to as the Kolwezian phase of the Lufilian Orogeny (François, 1973b; 1974; Calen, 1981; Costier et al., 1992; Kamupuzu and Calleux, 1990) which resulted in the formation of thrust surfaces, nappes, and edifice at depth (Cahen, 1970; Costier et al., 1992; John et al., 2003). According to Calleux and Kamupuzu (1995), tectonic nappes have been detached at the base of the thrusts nappes and thus formed during this phase, facilitated by decompression and slab rollback associated with the Rovuma and Djebel subgroups.

Continental–oceanic collision between the Congo and Kalahari Cratons occurred at ca. 530 Ma when tectonic white-cherts (white-cherts) formed under high pressure amphibolite facies conditions (John et al., 2004). The 530 ± 1 Ma Nd-Ne garnet-whole rock age of John et al. (2004) for the peak stage of metamorphism is also consistent with the 530 ± 1 Ma Nd-Ne garnet-whole rock age of Le Roux et al. (2004). Continental collision at ca. 530 Ma corresponds to the Mio-Lower Pliocene phase of the Lufilian Orogeny (Emevasa et al., 1997; Kamupuzu and Calleux, 1990) which resulted in northwest–northeast-directed thrusting in the western and eastern arms of the Lufilian Arc, respectively (John et al., 2001), as well as the formations of white-cherts, duplication of basement cover sequences through obduction folding and remobilization of uranium mineralization along reactivated strike-slip faults (Costier et al., 1992; Le Roux et al., 1997; Kamupuzu and Calleux, 1990; John et al., 2004).

Tectonic uplift and rapid erosion followed final collision and resulted in the deposition of rippled siltstones of the Bako Group Subgroup (Master et al., 2005) which is interpreted as a continental sequence (Kamupuzu and Calleux, 1989; Wendoff, 2003). Siltstones of the Bako Group are not metamorphosed and represent the youngest unit of the Katanga Supergroup with a maximum age of 571 ± 3 Ma based on 207Pb/206Pb dating of detrital muscovite grains (Master et al., 2005). Cooling ages range from 712 ± 470 Ma determined by K-Ar, Rb-Sr dating of muscovite and biotite from the Dombé region (Costier et al., 1992; John et al., 2004), represent the final post-metamorphic ages in the Lufilian Arc. Precise dating of the third phase of the Lufilian Orogeny, the Paleozoic-Chiroomwe phase of Kamupuzu and Calleux (1990) is not available. It is bracketed by the ca. 530 Ma collision event and the 512 Ma cooling age of granites in the Dombé Region. The Chiroomwe phase is represented by open systems and structures transtensive to the thrusts in the Lufilian Arc (Costier et al., 1992; Kamupuzu and Calleux, 1998).

In summary, the sequence of the Katanga Rhakonkong and Lufilian orogenic event Wendoff (2003) has proposed an additional younger Himalodian unit, the Fungurume Group, which is a sedimentary synorogenic complex of continental red beds (Mubwima Formation), marginal marine carbonates (Djebet Formation) and clastic detritus (Katombwa Formation) formed by basin gravity flow and erosion of the advancing thrust sheets during the Lufilian Orogeny, and deposited as detritus in the Katangan foreland basin (Wendoff, 2003a,b). According to Wendoff (2003), the Fungurume Group is partly coeval with the Bako Subgroup. Although the debate on the Katangan tectonic regime迄今outside the scope of this paper, it is worth noting that both previous and recent data pertaining to structural, lithological, petrographic, geochronological, geophysical and geochronological studies (e.g., Demasseva et al., 1983; Calleux and Kamupuzu, 1995; Kamupuzu and Calleux, 1998; Jackson et al., 2003; Calleux et al., 2005a,b; Kamupuzu et al., 2005; Batulle, et al., 2007) and unpublished C-O isotopic data (AMMA, project 872, final sponsors meeting of October 2008), provide evidence for a good
correlation of the Roan succession in both Congo and Zambia that strongly contradicts this interpretation.

Stratigraphic gaps between the Roan subgroups have been attributed to former magmatites (Calteux, 1981, 1994; De Magule and François, 1988; Calteux and Kampanza, 1995) and the role of salt diapirs in the genesis of some Copperbelt deposits, including the Kipushi deposit in Congo, has been suggested by some workers (e.g., François, 1978; Calteux, 1983; De Magule and François, 1988). Jackson et al. (2003) have gone further to propose that allochthonous salt tectonics may explain the occurrence of the enigmatic mega- and gigabreccias on the Copperbelt which underlie 25,000 km² and contain gigantostructures up to 10 km wide. According to Jackson et al. (2003), salt tectonics that began during deposition of the Roan Group, initially caused emplacement of evaporite-megabreccias and evaporitic diapirs into underlying strata and later resulted in northward extrusion of evaporite and carbonate-dominated sediments and ores over allochthonous strata during Lufilian deformation, and eventually culminated in emplacement of large thrust sheets.

2.3 Stratiform copper mineralization in the Katanga Supergroup

Economic deposits of the Neoproterozoic stratiform Cu-Co ores in the Lufilian Arc are found in different host rocks of the Mendedo/R.T. Kivwe/Mines and Kirilimbwwe/Dijeta subgroups (Table 1) with the most important rocks or carbonate dominated allochthonous units of the mines subgroup. The Cu-Co ores in Congo and within allochthonous units (sandstone, siltstone, mudstone and shale) of the laterally equivalent Kivwe subgroup in Zambia (Mendelson, 1981; Binda, 1994; François, 1974; Lebeau, 1974; Fröhlicher et al., 1976; Calteux et al., 2005b, 2007). The genesis of these deposits has been debated by several workers for many decades (see review in Sweeney et al., 1991) and although genetic hypotheses ranging from synorogenic to epigenetic (McGowan et al., 2005) still exist, a mineralized Paleoproterozoic basenem with copper-bearing greisens (Voigt and Freeman, 1972) and porphyry type copper deposits (Wakefield, 1978) is the most plausible source of deposit material for the ore-bearing units. Ore formation involved multi-stage syngenetic and early to late diagenetic processes of metal concentration from basinal brines, with some remobilization during orogenic metamorphism (e.g., Carlick, 1961; Frenzel, 1974; Calteux, 1983; Sweeney et al., 1985, 1991; Ansell, 1988a; Binda, 1994; Calteux et al., 2005b; Solley et al., 2005). The syngenetic-diagenetic mineralization is supported by microthermometric studies of pre-ore, syn-ore, and post-ore inclusions in gangue minerals which show that the ore fluids varied from low-temperature (70 to 156 °C) basinal brines to high-temperature metamorphic fluids (230 to 400 °C) with variable salinities (≤ 0.5 to > 14 wt.% NaCl equivalent) (Prainov, 1972; Rgagana, 1975; Audouville, 1982; Sweeney, 1987; Richards et al., 1983a, 1983b; Ansell, 1988; Gregory et al., 2005, F. Deschênes et al., 2007, 2008).

The stratiform Cu-Co ores in the Lufilian Arc are different from the carbonate-hosted Zn-Pb-(Cu)-(V) deposits which are the main focus of this paper by being stratiform, laterally extensive (hundreds of
metres long) syndiagenetic in origin and containing little or no Zn and Pb. In contrast, carbonatite-hosted Zn-Pb-(Cu)-(V) deposits and prospectococcar mermaid as irregular pipe- to vein-like bodies involving xenolithic zones of the tuffite and ankerite, the Zambesi and Malombeke belts as well as the Kudzundza, Adua, or salla (Fig. 2). They include the major epigenetic Ekipashi and Kabwo sulphide deposits which are hosted in carbonate units of the Ngwa Group in Congo and the Kipanda Formation Subgroup in Zambia, respectively. Metal concentrations vary from dominantly Zn-Pb to either Pb or Zn-rich occurrences, including the notorious willmore Zn prospects in the Lebala area (prospect 7, 8, and 9 in Fig. 2).

3. Description of the Zn-Pb-Cu ore deposits in the Central African Copperbelt

3.1. Deposits in Congo

Most of the Zn-Pb-Cu deposits in Congo are hosted in carbonate units of the Kipanda, Katavine, Kipushi and Katwe formations of the Ngwa Group (Table 1).

The Kipanda Formation, as defined informally by Icnicole (1982), corresponds broadly to the "Formation des Argiles de Kipanda et du Foss Faut Calcic de Kipanda" of Surfard (1978, 1988). It includes finely (mattstone) bedded, greenish (fresh rocks) or yellow to reddish (altered rock) dolomitic shales or chalky dolomites (e.g., in the Lulua area), evolving laterally into finely laminated and fine-grained dolomitic sandstones and sandy shales (e.g., in the Msheke-Bunkanga area). Fig. 3) At Kipushi, this formation is up to ca. 150-m thick and consists predominantly of dolomite rocks, while dolomitic argillaceous to sandy shales form the matrix of the host dolomite. A major horizon of argillaceous dolomite, termed "domite Tigere" (Tigere Dolomite), occurs at the base of the Kipanda Formation (Froissard, 1974; Icnicole and Osterboch, 1974; Surfard, 1974, 1988; Icnicole, 1982; Baranek, et al., 2007). The "Dolomite Tigere" is a finely laminated blue, gray to dark gray, fine-grained calcareous dolomite, calcareous in places, dark, torted, lenticular chert and dolomitic layers alternating with lighter dolomitic layers forming the tiger texture and commonly highlight slumping structures in this dolostone.

The Katavine Formation, up to 340-m thick (e.g., at Kipushi), is a regional marker horizon representing an epigenetic-rich dolomite and shale succession typical of an intertidal environment (Surfard, 1978, 1988), subdivided into three sub-units at Kipushi (Intomane, 1986, 1988). The lower unit includes pyrite-rich, light grey massive dolomite with relics and pseudomorphs after pyrrhotite, carbonaceous matter, and tourmaline (textural molds) dark layers referred to as "fluidal texture" by the mining geologists. The middle unit includes massive to finely bedded, light grey to pale grey, pseudo-sillotic calcareous dolomites. Petrographically, these rocks include micritic mudstone, inter-spaces, pelitic, and quartzites, and oncolitic debris forming a dolomitic-side-structure breccia (Surfard, 1978, 1988). Well preserved oncites provide a marker horizon at the top of the middle Katavine unit. Some organic relics related to "Tentacula" (spicula) type species were noted (Lacour, 1933). Minor disseminated strataform pyrite and chalcopyrite occur in this middle unit, which also contains antimony and pyrrhotite relics. The upper Katavine unit is a dark gray, crystalline, calcite- and carbonaceous dolomite with interbeds of fine carbonaceous layers and black clasts.

The Katwe Formation is overlain by the Kipushi Formation, a finely bedded, black carbonaceous dolomite unit, up to 150-m thick (e.g., at Kipushi), characterized by black shaly lenses and whitish oncites, slump structures, lenticular grey-brown dolomite shale (Surfard, 1978, 1982, Intomane, et al., 2007). The scoyelitic Katwe Formation in the southern area (also named "vsiro recirculus") by the mining geologists in Kipushi) contrasts with the Katwe Formation by the occurrence of laminated, pyrite, and whitish, albitite-bearing carbonates and talcose dolomite with intercalations of grey-green to dark grey shale bands, indicating alternating oxidizing and reducing environments during deposition. At Kipushi, sulphides (mostly pyrite, chalcopyrite, and bornite) occur along the carbonate beds. A sketch or fracture, which is displayed by the trend of take-alite-cuartz lenses in this shaly unit, with the sulphide grains elongated parallel to the cleavage. The Kipushi and Shire Recurrence

Fig. 4. Geological map in the Kipushi area (modified from Calkins, geological map, 1971).
Formations have a total thickness of ca. 330 m in the southern part of the Copperbelt (e.g., at Kipushi) but pinch out to less than 1 m in towards the north (e.g., at Kolomiti).

2.1. Kipushi

Kipushi (Figs. 2 and 3) is the most significant Zn-(Cu)-Pb carbonate-hosted deposit in the Copperbelt of Central Africa with total metal production of 5,622,115 tons Zn and 4,082,273 tons Cu from 1922 to 1993 when operations were suspended. The in-situ ore grades averaged 11.0 wt.% Zn and 0.90 wt.% Cu. Ore has been proven to a depth of 1,800 m but mine development stopped at 1,250 m depth. The remaining ore resources down to the 1,500 m level are estimated at >1.9M Zn and >400,000 tons Cu, and >160,000 tons Pb from ores averaging 21.4 wt.% Zn, 2.1 wt.% Cu and 0.88 wt.% Pb with additional ore reserves at 100,000,000 tons Cu and 10,000,000 tons Pb. Ag: (28 ppm) and Bi: (3 ppm) (Caillieux, 1981, 1992). Other rare metals include Au, Cd, Mo, Bi, Ag, Sn, Sb, Se, Sn, Te and U (Bos, H. et al., 1974; Timoniale et al., 1998).

The Kipushi deposit is hosted on the northern flank of a regional NW-striking antiformal characterized by a truncated antiform trenched with a megabreccia (the “Axial Breccia”; Fig. 4). The dip is 63°-73° SW on the southern flank and 75°-85° NE on the northern flank. The Axial Breccia is barren and consists of a heterogeneous layer-parallel breccia with highly strained and brecciated or rounded fragments of Roan and Nguba Group rocks (e.g., arkoses, sandstones, metamorphic rocks associated with white talc dolomite of the Kipeta Subgroup, and roods of the Kolomiti Formation) (Bailat, 1981; Timoniale, 1991). The dilomite of the Kipeta Subgroup and associated metamorphic rocks are typical of the Cambrian-type lithofacies unit (Caillieux et al., 1994, 1995). The Axial Breccia is either breccia type that generally underlies the Kolomiti Formation and interpreted as a result of the folding (F2) and thrust phase of the Luzuban orogeny (Bos, H. et al., 1974; Timoniale and Oosthoek, 1974; Caillieux and Kampusz, 1995; Kampusz and Caillieux, 1996).

The orebody is located along a northeast-trending fault, the Kipushi fault, which is associated with a second breccia type known as the “Cyclopean Breccia” on the hangingwall (Figs. 5 and 6). Geometrical relationships indicate that the “Cyclopean Breccia” cross-cuts the Axial Breccia and post-dates the axial fault (Timoniale and Oosthoek, 1997). The Kipushi fault and cyclopean breccia is characterized by branching pattern in plane view and mostly contains fragments of the enclosing dolomites of the Koshi and Kolomiti formations. Some breccia, similar to cyclopean breccia, and contains fragments of reddish-brown ironstones, with a yellow indurated matrix made of montomorionite. The pipe-like main body is irregular and elliptical in cross-section with a axial trend of 023° NE, 200 m long and 20 to 50 m thick with an average dip of 70° NW (Fig. 6). The breccia generally occurs along the Kipushi fault and forms discordant to the host rock within the cap carbonates of the Kolomiti and Kipushi formations, whereas it is largely sub-concordant in the alternating dolomite shales and dolomites of the Katare Formation.
The wallrock dolomites are sub-economic to barren close to the orebodies, containing only very finely disseminated diagenetic sulphides. The hangingwall of the orebody is formed by the "Grand Lambeau" (Fig. 5), a low-scale block of stratified carbonate-rich shales, siltstones and fine-grained sandstones of the Klubo Formation (Kandelungu Group) encased in the "Cyclopean Breccia" (Intomale, 1982).

Deformation features in the primary ores are highlighted by microfoliation in the banded ores (Intomale, 1982), pressure shadows along the NW-SE trending cleavage of the sulphide crystals (Chabu, 1990), and locally, cataclastic textures in the sulphides (Intomale, 1982; Chabu, 1990).

Features indicating hydrothermal alteration in the Klubuzi deposit include: (1) foliation of the Kalonwe limestone over an alteration of 200 m from the pipe (Thomass, 1926; Masty, 1931; Legay, 1931; Vaene and Moreau, 1931; De Vis et al., 1978; Demarque, 1974; Intomale and Oosterbosch, 1974; Intomale, 1982; Briquet, 1984; Francotte, 1985). The primary ore sulphide minerals include, in order of decreasing abundance: sphalerite, chalcopyrite, bornite, chalcocite, pyrite, arsenopyrite, enargite, and galena, with accessory biotite, garnet, mnisite, hydrated arsénille, carnotite, asbolane, lasalite, wallerite, molybdenite, galile, calafite, biotethinite, tungstenite, and stannosylvite (Intomale and Oosterbosch, 1974). Secondary supergene minerals that occur in the superficial oxidized
zone of the deposit and are not relevant for genetic interpretations, include: analcite, melanite, smithsonite, calamine, cuprite, chalcocite and, accessory, zincite-hydrozincite, aurichalcite, azurite, brochantite, chalcopyrite, heazlewoodite, anglesite, vesuvian, pseudomalachite, goyazite, canastraite, cuprospezicate, azurite, digenite, thymioska, willemite, native copper and silver (intraplate and Oxtreyenbach, 1974).

The diverse and complex mineralogy of the primary sulphides may broadly be grouped into five categories of ores, as defined by the local mining geologists:

(1) Zinc ore with a simple mineralogy consisting of Cu-rich sphalerite + pyrite + arsenopyrite + galena + tetrahedrite + chalcopyrite + galena. This ore type contains ≤7 wt.% Zn and ≥0.3 to 3.0 Pb, with Cu = 2.0 wt.%.

(2) Zn-Pb ore with a simple mineralogy including brown to dark brown sphalerite (36–67 wt.% Fe) + pyrite + galena + gallite + tennantite + chalcocite. This ore type contains ≥7 wt.% Zn and ≥0.3 wt.% Pb, with Cu ≤ 2.0 wt.%.

(3) Cu-Pb ore containing chalcopyrite, bornite, sphalerite, tennantite, pyrite, pyrrhotite + arsenopyrite + galena and ± tungstenite. Variations in the relative proportions of chalcopyrite and bornite result in the definition of chalcopyrite-type and bornite-type ores. However, bornite-rich ore disappears below the 1300 m level.

(4) Zn-Cu–Pb ores (the "mixed ore" of the mining geologists) contain ≤7 wt.% Zn, ≤7.0 wt.% Cu, and ≥0.3 to 3.0 Pb. The mineralogy is very complex and reflects the combination of Cu-rich and Zn-Pb-rich ores as described above.

(5) Massive pyrite.
The different ore types show a coherent zonal distribution with respect to host lithologies (Kipushi, 1982). The pipe-like body is characterized by: (1) predominantly Cu-rich ones in shales and carbonates of the Katite Formation in the northern part of the deposit; (2) Zn–Cu-rich ores in carbonates of the Kipushi Formation; (3) Zn-rich ores at the base of the Kipushi Formation and Zn–Pb-rich ores at the top of the Kakonthe Formation; (4) localized Zn–Cu or Cu ore masses parallel to the Kipushi Fault in the central to lower carbonates of the Kakonthe Formation and locally in the "Cyclopeat breccia"; (5) Zn–Pb ores rimmed by massive pyrite and arsenopyrite (generally convoluted into ore zones with pyrite and hematite in the superficial oxide zone). The latter ores occur as "chimneys" cross-cutting the Kakonthe Formation along north–south-oriented fractures parallel to the northern part of the Kipushi Fault (Fig. 10). The Kpakonda Formation contains massive pyrite, but also sub-economic disseminated pyrite. The zonal distribution of the Kipushi deposit can be traced in the "Cyclopeat breccia" below the 950 m level (Figs. 9 and 10). The main pipe-like body diverges into a central Zn or Zn–Cu–Pb–rich branch and an external Zn–Pb-rich branch. Below the 1350 m level, the concentration of Zn in the Zn–Cu ores decreases while the amount of Zn progressively increases. In general, the distribution of the ores indicates that Zn and Pb are preferentially hosted in impure carbonate lithologies containing some MnO (3 to 10 wt%).

The distribution of cobalt amounts down to the 1000 m level in a range of 200–300 ppm in ores from the northern part of the deposit (associated with the Katite and Kipushi formations), while ores from the southern part (associated with the Kakonthe Formation) average 50 ppm cobalt (Kipushi, 1982). Moreover, between 1500 and 1600 m levels (Calhoun, 1988) chalcopyrite mostly associated with copper ores, with average amounts of 165 and 115 ppm in the Cu, Zn–Cu, and Zn ores, respectively, in the northern part of the deposit (global average of 165 ppm), compared to values of 47 and 54 ppm in the southern part (global average of 59 ppm).
Panarctic studies of the ores show the following general sequence of ore deposition, from the earliest to the latest sulphides (De Keers, 1974): (1) pyrite-arsenopyrite; (2) sphalerite; (3) galena-tennantite-gemarganite-situellite; (4) bornite-chalcopyrite; (5) silver-bearing bornite. Based on the chemical composition of the sulphides and their parageneses, Ildefonse and Gutscherbich (1974) suggested the occurrence of two major successive primary mineralizing phases: (1) a Fe-As-Zn phase associated with minor Cu, Bi, Ge, and Ga; and (2) a Cu-Ag-bearing pyrite phase. The Fe-As-Zn phase resulted in the crystallization of Fe-As and Zn sulphides and terminated with precipitation of galena, whereas the second Cu-Ag-bearing phase involved replacement of earlier sulphides and precipitation of tennantite, Bi-, Ga-, and Ge-bearing chalcopyrite (Cu-bearing) sphalerite, galena, tourait, and cerusite. The intergrowth of these two mineralizing phases ultimately resulted in the formation of mixed Zn-Cu-(Pb) ores characteristic of the typical complex primary sulphide mineralogy at Kipushi.

3.1.2. Kenge re

Kenge re is located ~50 km south of Kivwebo and is the westernmost Zn-Pb deposit of the Copperbelt in Congo (Figs. 2 and 3). It has been previously mined for Pb (15,000 t Pb) at 60 wt.% Pb up to 1949, and unmined resources amount to ca. 63,200 t Zn at 28.9 wt.% Zn and 7700 t Pb at 5.5 wt.% Pb (Carnicelli, 1959 and references therein).

The local lithotectonics of the mineralized zone includes the Kapeka, Kakanwe, and Kipushi formations (Table 1, Fig. 11). Both Kapanda and Kakanwe rocks are characterized by the occurrence of black arsenopyrite-orewogi matrix, and the barren Kipushi Formation is locally affected by fracturing and minor quartz-carnotite recrystallization. The deposit is associated with a north-trending fault (Fig. 11) cutting across Ngama Group rocks (Moelle, Kapanda, Kakanwe, and Kipushi formations) and is located ~2 km south of a major NE-SW trending fault zone with a large breccia (Fig. 10). The major fault zone is subparallel to the axial planes of folds in the area.

The Kenge ore deposit is hosted in fractured carbonate rocks and breccias developed in the contact zone between the Kapanda and Kakanwe Formations and it plunges out at ca. 10 m depth (Figs. 11 and 12). The ore bodies consist of primary ore with dark brown sphalerite, pyrite, and galena, partly surrounded by 1 to 2-m thick Pb-rich oxide ore grading up to 60 wt.% Pb. The ore show the following primary paragenetic sequence from the earliest to the latest sulphides (Ildefonse, 1982): pyrite, Fe-As-bearing bornite, and Ag-bearing galena, based on the chemical composition of the sulphides and their parageneses. Ildefonse (1982) suggested the occurrence of two major successive primary mineralizing phases: (1) a Fe-rich phase characterized by crystallization of pyrite; and (2) a Zn-Fe-Pb phase with associated minor Cu and Ag during which sphalerite and galena were formed. The sulphides have been altered into secondary Zn-Pb-(G) oxide minerals (cerussite, smithsonite, calamine, and locally traces of chrysocolla) in the superficial oxide zone.

3.1.3. Lume re

This Zn-Pb deposit is located in the central-northern part of the Congo Copperbelt (Figs. 2 and 3) along a fault in the contact zone between the Krame and Kipushi formations (Fig. 13). A major NE-SW trending fault zone associated with the Musende deposit and located ca. 17 km south of the Lume re deposit (Fig. 15). This major fault zone contains metasomatic rocks of the Dibeta Subgroup. Ore resources down to
a depth of 65 m below the surface amount to ca. 9300 tons at 3 wt% Zn and 1950 tons at 1.4 wt% Pb (Callieux, 1989). Lenticular sub-economic (<1 wt% Pb) zones of pyrometasomatic alteration of the breccia and breccia occur in the upper beds of the Katiyo Formation (Ittonmale, 1982).

The main orebody at Tonkine is hosted in tectonized carbonates of the Kipushi Formation, that contain impregnations of black amorphous organic matter. The orebody is up to 10 m thick, lenticular, and concordant with the dip of the host rock. It pinches out at a depth of 65 m (Ittonmale, 1982; Callieux, 1989). A second orebody was intersected at ca. 35 m depth below a reverse fault (Fig. 14).

The ores show the following primary paragenesis from the earliest to the latest sulphides (Ittonmale, 1982): pyrite, sphalerite, tennantite, cinnabar, galena, chalcopyrite, sphalerite, and chalcopyrite, then on to galena. The orebody is defined by the following elements: Zn, Pb, Cu, Ag, and Au.

Fig. 11. Geological surface map of the Kengere area (modified from Ittonmale, 1982; François, 1965; Callieux, 1989).

Fig. 12. Map view of the Kengere ore deposit stratigraphy and structural features at cross-section X: +60 (modified from Ittonmale, 1982; François, 1965; Callieux, 1989).
Fig. 13. Geological surface map of the Lombe area (modified from Intumule, 1982; Rampele, 1983; Calleux, 1983).

an unidentified Pb-As sulphide, galena, skutterudite and arsenocovellite. Based on the chemical composition of the sulphides and their parageneses, Intumule (1982) suggested the occurrence of two major successive primary mineralization phases: (1) an Fe phase forming pyrite; and (2) a Zn-Fe-Pb phase associated with minor Ag, Cd, Cu, and Ag with crystallization of the other sulphides. Cassiterite occurs as a secondary supergene phase associated with chalcopyrite. Other secondary Zn-Fe-Cu oxide minerals (carmalite, smithsonite, cerussite, malachite, azurite) formed through alteration of primary sulphides in the superficial oxide zone near the surface.

At Lombe, pyrometallurgical shadlocite and chalcopyrite have formed lenses as limnicific sub-economic (≤ 1 wt% Cu) bodies hosted in the upper beds of the Katete Siente Formation (Intumule, 1982).

3.3.4 Other similar occurrences in Zambia

Dibalashi, located ~20 km to the west of the Lombe Mine, is in the northeastern part of the Luflian Foldbelt, is a low-temperature hydrothermal Cu, Zn, Pb, and Ag ore deposit with >15,000 tons Cu and 537 tons Ag (Lummen et al., 2003). The ores deposited in a complex set of three groups of faults that created favoursite conditions for mineralizing fluids circulation (Haest et al., 2005). A late intense fracturing is related to the D-1 and/or B-2 deformation events of the Luflian orogeny (according to Kampaeta and Callais, 1995). Two generations of sulphides were identified (Dewarte et al., 2003; Haest et al., 2003; Haest et al., 2001): (1) arsenic-rich pyrite; (2) chalcopyrite, enargite, and chalcocite; (3) malachite and azurite; and (4) chalcopyrite, enargite, and chalcocite. These assemblages were identified in the intersections of mineral veins and breccias in the upper beds of the Munongwe Formation rocks of the Kufwe River Group (Table 1) probably related to a D-1 and-deformation. The chalcopyrite-dominated and economically most important second generation of vein-type ore developed within a complex of faults in sandstones interbedded with argillites and intramammalian breccias of the Munongwe and Chiulo Formations (Lummen et al., 2003; Randa Nicholas et al., 2003; Dewarte et al., 2004; Haest et al., 2003). In the superficial zone, these sulphides are altered to secondary oxide minerals (malachite, chrysocolla, and azurite). This deposit is interpreted as similar to the Zn-Pb-Cu deposits in the copperbelt (Kanda Nicholas et al., 2004; this paper).

Several authors (Van Aubel, 1928; Ineckra, 1976; Intumule, 1982; Calleux, 1983) have reported Zn-Pb occurrences in the Roan Group at.

Fig. 14. Map view of the Lombe ore deposit, stratigraphy and structural features at intersection X: 0 (modified from Intumule, 1983; Rampele, 1983; Rampele, 1992; Calleux, 1983).
Mohwagwadi, Kapinga, Kabunde, and Minasi (Fig. 9) are generally hosted in quartz-dolomite veinslet composed of sphalerite-galena with associated pyrite and traces of chalcopyrite, or aspyrite-rich remnants containing only a few percent of Zn and Cu. However, unlike the Zn-Pb mineralization in the Kapinga and Kabunde Conglomerate, no significant sub-economic deposit is known in the Roan Group in Congo.

Implications of outcrops high grade iron oxide are (mostly hematite) are hosted in carbonates of the Kalambo Formation (e.g., Kikongo, Katwa, Lubilula deposits; transact, 1984). Kikongo located close to Kambwe, consists of two main types: (a) red beds, 5 to 25 m thick, and (b) a 100-m-thick high manganese zone. The ore includes trace amounts of Cu, Co, Zn, and Au, with relics of pyrite in depth. There are oxide deposits probably represent gosain formed by the alteration of massive primary pyrite during diagenetic and later weathering, and the origin of this pyrite could be related to identical genetic processes that deposited pyrite associated to the Zn-Cu-Pb deposits.

3.2. Depots in Zambia

3.2.1. Kabwe deposit

Kabwe (previously named “Broken Hill”) is the most significant Zn-Pb deposit in Zambia. It is located about 110 km north of Lusaka, within a region that includes a cluster of Pb, Zn, Cu, and Au deposits (Fig. 10). According to the local geologists (Taylor, 1954; Whyte, 1961; Kambwa, 1963) and to a recent review (Kambwa and Friedrich, 2007), the Neoproterozoic lithostratigraphic of the Kabwe area includes, from the base to the top:

1. A basal conglomerate resting unconformably on a Paleozoic-Mesoproterozoic basement complex largely made up of lesser granite-gneiss and younger Musa schist and quartzite as well as intruded diorite (Taylor, 1954).
2. A mixed unit known as the Kabwe deposits (Monier, 1964; Carney and Kerr, 1998) consisting of limestone, quartzite, and conglomerates at the base and overlying metasediments, chlorite, phylite, and dolomite at the top.
3. A predominantly phyllite-dolomite unit with associated calcite-keatite named the Nyanza Formation.

As discussed by Kambwa and Friedrich (2007) the lower units of the Kambwa Formation have been correlated to the Lower Roan of the Upper Roan and the upper units to the Upper Roan. The Kambwa Formation is part of the Kambwa subgroup and is equivalent to the Kambwe and Banketa Formations in Table 1. As mentioned above, the Kambwa Formation has been subdivided into the following units: west (Kambwa, 1972), a gray arenaceous dolomite; (b) a light gray massive dolomite hosting the main orebodies; (c) a gray slightly carbonaceous dolomite; (d) a dark carbonaceous dolomite; and (e) a gray argillite and a pelitic dolomite with talcose partings. The Nyanza Formation has been correlated to the Nyanza Group (Monier, 1964; Ironside, 1982), but it is also possible that it is equivalent to the Upper Roan, as indicated by the structural and geochemical data of Raj et al. (1978) for the Lusaka Dolomite, which is presumably equivalent to the Nyanza Formation.

Nguba equivalent lithostratigraphic units at Kabwe have been observed by Taylor (1954), Kambwa (1972), and Ironside (1982). Ironside (1982) identified the following Nguba equivalent lithostratigraphic units in drill core Sp 128 from Kabwe, from base to top:

(a) a matrix-supported conglomerate corresponding to the “Grand Conglomérate” (Musha Formation) (Table 1); (b) a finely bedded dolomitic alternating with carbonate-rich and carbonaceous shales, the “Dolomieu Dolomitique” showing trachy features similar to the “Dolomieu Tétrique” marker horizon in Congo; (c) a gray to dark gray bedded dolomite including nodular carbonaceous shales (“Carbonaceous Dolomieu”); (d) light gray massive dolomite with frequent zones of rhyolitized dolomite and locally fractured at the base. In this convention, the “Schistes” and “Conglome” dolomites are interpreted as part of the Kabwe Formation. The upper Kabwe dolomite may thus correspond to dolomites of the Kabwe
Formation. However, the Njuba units intersected by drilling occur along the Mine Chib fault zone (Taylor, 1954) and have been intersected in the Erbog Nyaba units (Karmanta, 1972).

The Njuba ore bodies consist of Pb, Zn, Ag, Cu and Sn over a period of 88 years (1905 to 1993) from a re-processing ore tonnage of 12.28 Mt averaging 25 wt% Zn and 10.7 wt% Pb (Karmanta, 1983; Karmanta and Friedman, 2007). At mine closure in 1993, the remaining resources, largely in the No. 2 zinc-sulphide orebody, were assayed at ~19 Mt at 12.13 wt% Zn and 1.5 wt% Pb. The relatively rare trace elements of Cu, Fe, and Au have been removed from the ore since the ge-bearing sulphides of enstatite and bronzite were only discovered in 1998 (Karmanta et al., 1999; Karmanta, 1993), from which time most of the ge-bearing massive Zn-Pb ore has been almost mined out. Further investigations are required to establish the possibility of encountering trace metals such as Cu, Fe, and Au from the slag heaps.

Zn-Pb mineralization in the Njuba area includes massive, disseminated, and stringer types (Karmanta, 1993). The main massive Pb-Zn ore bodies occur mostly in the massive dolomite of the Bancroft Formation, but disseminated mineralizations also occur in the overlying carbonaceous dolomite at Airfield (Karmanta and Friedman, 2007). Prospects with disseminated type of mineralization in dolomite include Carmanor, Lokal-Zn Milberg and Chiwanda (Fig. 13). The disseminated mineralization is also associated with an overlying lateritic horizon enriched in Zn, Pb, and V as found at Airfield, Carmanor and Chiwanda.

The Njuba deposit consists of massive Pb-Zn ore bodies (Fig. 15) containing galena, sphalerite, pyrite, minor chalcopyrite, accessory brucite and sericite that collectively constitute the primary ore mineral assemblage (Karmanta, 1993; Karmanta and Friedman, 2007). The orebodies are surrounded by a wide zone of silicate ore (sericite) and mineralized jasperoid that consists largely of quartz, willemite, cerussite, smithsonite, goethite and hematite, as well as numerous other secondary minerals, including vandrites, phylloclades and carbonates of Zn, Pb, Cu and Sn. These orebodies are hosted in the massive dolomite close to the faulted contact with a schistose talc-bearing dolomite (Fig. 15).

Detailed descriptions of the individual orebodies at Njuba, including the morphology of the individual orebodies and their structural setting, mineralogy, sulphur isotope geochemistry, and preliminary results of fluid inclusion studies have recently been provided by Karmanta and Friedman (2007). The massive orebodies mainly occur along NE-SW trending faults as shown by the strike of the Njuba ore body (108°) which is subparallel to that of the No. 3/4 orebody (Fig. 17). The orebodies are clearly discordant to the host dolomite which has a local strike and dip of 280°/65°NE. The orebodies are associated with a cemented breccia and are intruded by the Mine Chib fault zone (Fig. 17). The No. 3/4 orebody (Figs. 13 and 18) is the largest single orebody at Njuba with a total ore production of 5.3 million tonnes (Mt) and average grades of 28.8 wt% Zn and 15.1 wt% Pb (Karmanta and Friedman, 2007). The pipe-like orebody is typical of other major orebodies at Eshuana, but it carries chalcocrite-like (arsen-stibite) haloes of the 1050 ft level (Fig. 18). The shallow plunging nature of the orebodies is also observed in the No. 1 and the No. 3/4 orebodies (Fig. 17). The pockets of disseminated mineralization shown in Fig. 17 were delineated by diamond drilling. The wallrock dolomite is barren of ore minerals, but it may contain very finely disseminated diagnostic sulphides of galena, cerussite and pyrite.

The Njuba deposit is also associated with breccia bodies as documented by Whyte (1965), Sturman (1972) and Samana et al. (1991). According to Samana et al. (1991), the main features of these breccia are characteristic of a hydrothermal origin. The collapse breccias are mantled by a lithified brown-yellow to reddish-brown mud matrix and can be seen to pass through breccialike breccia and fracture cutting the host rocks. The breccia fragments are lined with carbonates and/or ore minerals. The orebodies show a cross-cutting relationship to the surrounding rocks and stratification planes. However, the stratified incised matrix of the breccia is broadly parallel to the NW-SE trending in the host rocks. These features were used to indicate a pre-kinematic emplacement of the deposit (Samana et al., 1991) but, as at Njuba, they can also be interpreted to mark a syn-kinematic deposition.
Hydrothermal events in the deposit are outlined by:

(i) development of "jasperoid silicate ores" which mark the silicification of the host dolomites;
(ii) emplacement of massive pyrite ores, frequently converted into ironstone containing hematite and goethite (pseudomorphed after pyrite) and deposition of the no. 5/6 massive sulfides;
(iii) emplacement of a very coarse to giant-grained (crystals up to 1 m) white eck dolomite around the No. 8 orebody (Fig. 15) believed to be of hydrothermal origin (Kanoma, 1991, Kanoma et al., 1999; Freeman, 1981);
(iv) deposition of black organic matrix in the mineralized breccia.

Peak of massive sulfide deposits occur 0.5 m wide occur within the major orebodies, and the No. 8 orebody is composed entirely of sphalerite (Kanoma and Friedrich, 2007). Sphalerite generally contains low amounts of Fe (0.3–1.1 wt%), Mn (0.01–0.1 wt%), and some Cd (0.08–0.41 wt%). Galena is subordinate to sphalerite in the massive 2a. Phases (Nos. 1, 3, 3/4, 4, 5/6, and 5c orebodies) which have a Zn/ (Zn + Pb) metal ratio of 0.63. The amount of galena is less in the oxidized silicate ores (Nos. 2, 3, 50, 3, 2g/w, and roundy) which have an average Zn/(Zn + Pb) ratio of 0.88. Galena contains Bi (~0.05 wt%) and Ag (~1.03 wt%), whereas trace amounts of Cu (~0.01–0.11 wt%) and Ni (~0.02 wt%) occur in pyrite. Chalcopyrite is characterized by significant Ge (0.16–0.63 wt%) and low concentrations of Zn (~0.05 wt%). The Ge in chalcopyrite is due to the presence of exsolution intergrowths of riebeckite and bournonite which also occur as inclusions in pyrite, galena, and sphalerite (Kanoma and Friedrich, 2007).

Mineralization occurs locally in the sulfide ores and is typically caused by serpentine interbeds of galena–sphalerite or pyrite–sphalerite. Massive pyrite mineralization occurs marginal to some orebodies (e.g., 2 and 5/6 orebodies; Itambala, 1982; Kanoma, 1992) but also as oxidized fragments of ironstone (pseudomorphed after pyrite) in all the orebodies. It seems that massive pyrite was deposited at an earlier stage of sulfide emplacement (Taylor, 1952; Kanoma, 1993).

Fig. 3. Structural section through the N° 1, N° 3/4, and N° 5 orebodies at Kabwe mine (modified from Kanoma et al., 1990).

Fig. 18. Three dimensional view of the N° 5/6 orebody at Kabwe mine (based on mine data).
Numerous secondary and supergene minerals (Kanamasa et al., 1981a; Kanama, 1983 and references therein), that make Sabwe 
mineralogically famous include rare phosphates (tennantite, parahaskite, pyromorphite, hopite, speronite, scholzite, and zircon 
blendelite), nemalite (scombellite, alunite, nemalinite), clinozoisite 
(zinc blende, zirconium, ilmenite, chromite, magnetite, and 
iron sulfides), and wulfenite and cuprite (cuprite, wavelite, 
camaroonite, and copper). Sulfides (galena, pyrite, chalcopyrite, 
bornite, chalcocite, iron pyrite, and sulfur) are present in 
various proportions and occur in the form of disseminated 
mineralization, with the exception of pyrite, which is 
commonly found in the form of veins and fractures. The 
mineralization of the Zn-Pb-Cu deposits is typically 
controlled by a variety of factors, including tectonic 
activity, hydrothermal fluids, and migration pathways. 

4. Ore geochemistry

4.1. Mineral chemistry

Detailed accounts of the mineralogy of the Zn-Pb-Cu deposits in 
the Central African Copperbelt can be found in previous publications 
(e.g., Hubbard, 1981; Memeti, 1976; Tourin, 1986; Leprince, 1981; 
Muyu, 1983; Guillet, 1976; Fassotte et al., 1985; Whate, 1986; 
Vilimek, 1986; Frederik and Villers, 1986; De Vos et al., 1984; 
Dinante, 1974; Nortier and Kanamasa, 1986; Frederik and 
Vilimek, 1986; Blauwhood, 1986; Kanama and Friedel, 1986; 
Kanama et al., 1981b; Kanama, 1983; Fassotte, 1982). The most 
relevant data from these papers are used here and supplemented 
by recent work on drill core material from Kipushi (BRR, unpublished 
data).

Although many ore varieties may exist, the foliated set of 
minerals is typical of massive Zn-Pb sulfide ores, as in the 
low-grade metamorphic area of the Copperbelt of Central 
Africa. Sphalerite and galena are the dominant minerals, 
with minor amounts of chalcopyrite, pyrite, and bornite. 
Kanama and Friedel (1986) note that the Zn-Pb-Cu deposits 
in Kipushi are most complex in the copper zone, where the 
copper content is much higher (ca. 40% Cu) and the 
Pb-Zn (<5% Zn) concentrations. Pyrite is also 
commonly associated with these deposits.

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commonly associated with these deposits.
<0.2 wt.% Fe (range 0.3-1.9 wt.%) and, apart from rare inclusions of biotite and biotite-felsic rock, is usually devoid of olivine (Kumano and Osterhage, 1974; Kamona, 1981). At Kigushi, the Cu content in sphalerite varies from 0.02 to 2.2 wt.% (Mäkerle, unpublished data). Sphalerite also contains significant amounts of Cu (up to 0.68 wt.%) and/or Fe (from 20 to 820 ppm) (Kumano and Osterhage, 1974). A light green variety of sphalerite containing 3.5-6 wt.% Cu, 0.18 wt.% Fe, and 0.38-0.52% Ni has been observed only in association with Ge (in perilune) on Kigushi (Kumano and Osterhage, 1974). According to Hennings and Hennings (1990), this green colour is due to the presence of cobalt.

Pyrite composition is homogeneous in the different ore types (muscovite pyrite ore excluded), with a maximum As content of 0.5 wt.% at Kigushi and 0.25 wt.% at Kigushi. At Kigushi, amorphous pyrite contains pyrite inclusions in muscovite (up to 1.5%, Cu, 0.07 wt.%), and Ni (average 0.02 wt.%), and contents as well as the Co/Ni ratios (average 1.58; range 0.51-4.27) of pyrite from the Kigushi deposit. These values differ distinctly higher than the values documented in sedimentary pyrite (Co/Ni). The similar values are recorded by several workers (Luton, and Salomone, 1984; Campbell and Ebihara, 1984) in pyrite from hydrothermal deposits. Microprobe analyses of pyrite from Kigushi indicate elevated Cu (up to 1.1 wt.) and low Ni (<0.02 wt.%).

Galena is a major ore sulphide that, nevertheless, appears to have formed late in the paragenetic sequence. Composition of galena is uniform and, at Kigushi, its average content of Ag is 0.05 ± 0.01 wt.%. Chalcopyrite contains 0.19 ± 0.03 wt.% Ge, and the grains show exsolution intergrowth of biotite and pyrite (Kumano, 1981; Kamona and Friedrich, 1997). Both biotite and pyrite in the Kigushi massive sulphide ores contain inclusions of the other mineral, but homogeneous grains free of inclusions are also present. These rare biotite and pyrite grains occur as rounded to oval grains in pyrite, chalcopyrite, sphalerite, and galena in the massive ores. In the Kigushi deposit, biotite and pyrite occur in the mixed and Cu-rich ores (Kumano, 1982), often associated with galena, Ga-rich chalcopyrite and molybdenite. Sometimes biotite grains contain intergrowths of molybdenite, and Fe-rich tennantite is an important component of As (up to 1.2 wt.% at Kigushi) and may also contain Ga (up to 1.2 wt.%), and Ge (up to 0.11 wt.%). Boron is occasionally highly enriched in Ag (up to 9 wt.% in Kigushi), whereas tennantite contains Cu, Ge (up to 2.4 wt.%), and Mo (<0.5 wt.%). Camouflier, stanardite, germanonshaleite, biffingite and scheelite have rarely been identified as minor components of massive sulphide ores at Kigushi (Mäkerle, unpublished data).

The composition of molybdenite, germaninite, bismuthite, galena, Ga-rich chalcopyrite and germanonshaleite from different deposits are shown in Table 3. René et al. (1979) and Yamaoka et al. (1981) also observed that, in general, Cu content (as Cu, CuO and CuS) is common in deposits (up to 1.0 wt.%), whereas it is below detection limits at Kigushi. Bismuth, from Kigushi is also richer in As (up to 0.39 wt.% Cu) and Cu (0.44-4.46 wt.) than those from Kigushi (As: <0.2 wt, Cu: 36-39 wt.). Compared to tubemore, where the germaninite is the most abundant Ge phase, germaninite is rare at Kigushi, and is commonly replaced by renéite (as was noted in Table 1). Germanonshaleite was recently identified in drill core material from level 150 at Kigushi, where it is intimately intergrown with biotite and molybdenite, the mineral has previously been recognized as "Mineral Y" by Frink (1992). Germanonshaleite and okalite are common accessory phases at Kigushi Spings and Tumulus, respectively (Spindler et al., 1992; Mäkerle et al., 1993).

The mineral composition of mixed and Cu-rich ores from the Kigushi deposit is poorly documented. Textural relationships show the complex evolution marked by exsolution, microgrowth, exsolution of Cu and Zn-Rb minerals as well as Cu and Ge-Cu minerals in the mixed and Cu-rich ores (Yamaoka et al., 1981). These complex textural
features result from the commingling of distinct mineralizing fluids (see next section). Several of these textures indicate relatively rapid precipitation of sulphides, but the discordant chalcopyrite in the Cu-rich ore zone results in extensive leaching of previously deposited sulphides (Intumale, 1982). In the Zn-Pb-rich orebody, boronite coexists with pyrite and chalcopyrite above 1300 m depth, and only chalcopyrite-pyrite persist at greater depths. In the Kipushi deposit, the primary boronite is silver-in, in contact with the secondary minerals from the supergene zone (at 2300 m depth) (Intumale and Oostenbosch, 1974). Ascension (1975) showed that the stability fields for chalcocite (Cu2S), bornite (CuFeS2), and pyrite (FeS2) in the presence of Zn-Pb minerals are highly controlled by oxidation state (log (Fe2+/Fe3+)) and acidity (pH). According to experimentally derived solubility data, a mineralization marked by Cu2S→FeS2→ZnS→CuS at shallow levels can be explained by an ascending mineralizing fluid undergoing a decrease in Fe/S and/or pH. However, ascending hot fluids would result in the decrease of temperature and increase of Cu2S during the crystallization of sulphide ores. The conversion of pyrite into bornite occurs in the collapse breccias in the Zn-Pb deposits in the Copperbelt is evidence of this increase in Fe/S.

Ascending fluids result in a complex deposition of mixed ore at Kipushi, as shown by the diversified mineralogy defining several categories of ores. Underground mining has facilitated the determination of the composition of the ores between 300 m and 1600 m depth (Intumale, 1982). The vertical variation curves for Zn, Cu, Fe, and S in the Cu-rich ore zone (Fig. 19) show a general increasing trend for Cu, from bottom to top, whereas Fe indicates the reverse trend. These curves also show three sequences, notably 1 (between 875 and 2300 m), 2 (between 1200 and 1600 m), and 3 (between 1300 and 1700 m), characterized by a vertical zonation of the metals with maximum values of Zn at the top and a Cu-Zn mining zone at the base. It is noteworthy that maximum values of Cu occur within the Zn maximum zone in sequences 1 and 2. The shape of the curves suggests a more complete mixing of Cu and Zn at the base (CM in Fig. 19). If this is true, the Cu and Zn concentrations in barren pegmatite zones (Cu<50 ppm, Zn<500 ppm) as well as in carbonates of the Koo arn (Zn<100 ppm) are generally low. Higher contents of up to 13000 ppm Pb and up to 48000 ppm Zn were recorded in mineralized dolomites in epigenetic deposits located around the Kapwe deposit (Ramona, 1993). Hydrothermally-silicified rocks (*silicate ore* included), massive pyrite, Zn-Pb ores and Cu-Rich ores in the Zn-Pb zone shown, at Kipushi contain less than 50% Zn. In Congo, all the Zn-Pb ores are also poor in Cu, but up to 10000 ppm has been recorded in the Zn-rich, and 250-300 ppm in the Cu-rich (low Zn-Pb) ores hosted at the top of the Kakanwile formation and in

Fig. 19. Vertical variation curves for Zn, Cu, Fe, and S in the Cu-rich ore zone at Kipushi (modified from Intumale, 1982). IM: incomplete mixing; CM: complete mixing.
Table 4

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Kipushi</th>
<th>Lubenza</th>
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<td>Carbonates</td>
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<td>Major and minor elements (wt%)</td>
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<tr>
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<td>1.50-0.10</td>
<td>0.14-0.03</td>
<td>1.46-0.02</td>
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<td>Fe₂O₃</td>
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<td>0.06-0.01</td>
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<td>0.12-0.03</td>
<td>0.06-0.01</td>
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<td>0.16-0.04</td>
<td>0.25-0.06</td>
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<td>0.25-0.06</td>
<td>0.16-0.04</td>
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<td>CaO</td>
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<td>0.68-0.00</td>
<td>0.82-0.01</td>
<td>0.68-0.00</td>
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</tr>
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<td>K₂O</td>
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<td>0.35-0.00</td>
<td>0.44-0.06</td>
<td>0.35-0.00</td>
<td>0.44-0.06</td>
<td>0.35-0.00</td>
<td>0.44-0.06</td>
<td>0.35-0.00</td>
<td>0.44-0.06</td>
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<td>F₂O₃</td>
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<td>0.05-0.00</td>
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<td>0.05-0.00</td>
<td>0.02-0.03</td>
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</table>

the Katwe Formation at Kipushi (incorrectly and Drosbach 1974; BGR, unpublished data). In contrast, the Katende trend deposits of the Room Group contain high grades of caloid, i.e., 0.31 and 0.04 wt% Cu, on average, respectively in the Congo-type and Zambia-type facies, with a maximum of 2.59 and 1.8 wt% Cu, respectively (Caleti et al., 2008a). Gold shows significant values in the Congo-type Katende trend deposits whereas silver is important in Katende-type deposits. At Kipushi, up to 123 ppm Au were recently analyzed in drill core material (BGR, unpublished data).

4.2. Host rock geochemistry

The carbonate rocks hosting the Zn-Pb deposits both in Congo and Zambia have a dominantly composition, with 4.2 wt% MgO = 0.274 wt% Fe₂O₃ and 0.3 wt% CaO = 0.01 wt% Cu, on average (Table 4), while thick limestone beds (1.0 wt% MgO = 0.03 wt% Fe₂O₃ and 0.2 wt% CaO = 0.02 wt% Cu) alternating with dolomite occur in other areas (e.g., Lubena, south of Lubenza; Tastara, in the Shikole area; Katende, in the Likasi area; Table 5). High contents of MgO (4.2–0.2 wt% MgO) are also common in the Nguba Group dolomitic shales associated with the carbonates in the Katende deposits (BGR, 1982). Similarly, the Room Group is characterized by high MgO-rich rocks, a feature that Möhle et al. (1985) attributed to pre-metamorphic magmatic clay minerals in equigranular facies. The values of MgO and TFe₂O₃ (generally >1 wt%) in the Katende Group shales are generally higher than the averages (3.3 wt% MgO, 3.3 wt% TFe₂O₃) in polymetamorphic facies (Carmi and Holba, 1988). However, similar dolomitic shales associated with dolomites are known in several polymetamorphic deposits hosting Mg-MgNi Valley-type Zn-Pb deposits.

The host rocks and the gangue minerals in the low grade metamorphic zone commonly include carbonates, quartz, muscovite, chlorite, actinolite, and biotite. Talc occurs only in the host rocks (Chabu, 1990) and, as common biotite mineral (Bach and Boy, 1994), very little is substituted for muscovite (Ferry and Aplin, 1999; Xu et al., 1999). In the Katende, biotite-green F-rich MgNi-rich with 4.4 wt% Fe₂O₃ and 0.3 wt% CaO, in the sulphide-bearing assemblages and F-Mg poor (<0.1 wt% F) in the barren rocks. Talc occurs very rarely in the Katende. Chlorides are Mg-rich (Mg/(Mg + Fe) > 0.3) in the country rocks whereas they are Fe-rich (Mg/(Mg + Fe) < 0.3) in Zn-Pb ores. This suggests that the ore fluids were marked by higher X₉₈ values than fluids in the barren rocks; this is not in equilibrium with other chemical environments and this in turn explains the absence of this mineral in metamorphosed deposits. Mg-rich biotite, phlogopite, and talc are generally recorded in shales and many dolomites at several metamorphic and tectonic levels within the Copperbelt in Congo and Zambia, indicating extremely Mg-rich compositions of the sediments involved in the metamorphic process.

Phengitic muscovite is ubiquitous. At Kipushi, Chabu (1990) and Chabu et al. (1994) have reported biotite-muscovite (up to 7.26% K₂O) occurring in muscovite with 15.12% K₂O content and 15.12% K₂O content in the phengitic muscovite. Kipushi is not associated with phengitic muscovite and no such muscovite is detected in the metamorphic assemblages. Additionally, muscovite is more abundant in the phengitic muscovite, indicating that the muscovite is more abundant in the phengitic muscovite, indicating that the muscovite is more abundant in the phengitic muscovite.

5. Mineral geothermometry

The mineral assemblages in the host rocks at Kipushi and Lubenza reflect Cu-rich facies metamorphic conditions as indicated by talc-

Table 5

<table>
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<th>Kipushi</th>
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chlorite-albite, and the absence of tremolite in dolomites and
dolomitic shales. Tie is dolomites of orogenic belts is usually associated
with hydrothermal activity and is unstable in the low pressure regimes
of the kaolinite zone. The paragenesis of kaolinite, sericite, chlorite (Mg),
talc (K) and quartz (Q) in the Al-poor rocks. The dolomitic shales crystallized around the unvariant curve of the reaction
\[ 8\text{MgO} + 3\text{CaO} + 2\text{SiO}_2 + 4\text{H}_2\text{O} \rightarrow 5\text{MgAl}_2\text{Si}_2\text{O}_5 + 4\text{CaCO}_3 + 4\text{H}_2\text{O} \]
which is restricted to ca. 400–
412°C at a pressure of 1 kbar (Bucher and Frey, 1998). The occurrence of
talc and chlorite at the Tintuwee Zn occurrence marks a high pressure
regime and temperatures bracketed between 350°C at 1 kbar and
700°C at ca. 1 kbar.

Sphalerite geothermometry used on the Zn-rich ore pipes at Kip-
chik suggests temperatures of formation between 351 and 394°C
(Offenburg, 1980). The occurrence of sodic intergrowths between
calciophylite, biotite and amphibolite at the Kibow and Kipchik
indicate magmatic formation of these minerals from a high-temperature
parent Cu–Ge–Fe–S solid solution (Kanossa and Friedrich, 2007).
According to Talonen (1975), the p1-low temperature polymorphism of
calciophylite may contain up to 4 wt% biotite in solid solution at
430°C.

Sulphur isotopic fractionation between pyrite, sphalerite and galena,
consisting in apparent equilibrium at Kibow, yielded an isotopic
temperature of 450°C (Kanossa and Friedrich, 2007). Generally,
the isotopic enrichments in sulphides follow the equilibrium frac-
tionation trend pyrite-sphalerite-galena, but the isotopic tempera-
tures given by the sulphide pairs are variable. The sphalerite-pyrite
geothermometry yielded values in the range 140–170°C with a mean
isotopic fractionation effective of 2°C (Talonen and Kanossa, 2007).
In contrast, coexisting pyrite-galena (330–350°C) and sphalerite-galena (90–940°C) sulphide pairs both exhibit apparent
diagenetic conditions due to the generally late paragenetic position
of galena (Kanossa, 1993; Kanossa and Friedrich, 2007).

6. Fluid inclusions studies

Fluid inclusions investigated in the Zn-Pb deposit of Kibow and
Kipchik display similar characteristics. At Kibow (Kanossa and Friedrich,
2007), fluid inclusions in sphalerite, quartz and carbonate associated
with massive sulphide ores, vein mineralization and the wallrock
dolomite characterized by liquid + vapor + solid (L + S + V) and
liquid + vapor (L + V) phases were identified at high-temperature fluids (HTF) and low temperature fluids (LTF), respectively. The range
of homogenization temperatures (T hom) recorded in HTF inclusions is
250–350°C (average 320°C), whereas lower values of 90–180°C characterize the LTF inclusions. The salinity is higher in HTF inclusions
(up to 31 wt% NaCl equivalent) than in LTF inclusions (ca. 11.5 wt%
NaCl equivalent). At Kipchik (Ishijima et al., 2008), fluid inclusions in tourmaline and quartz associated with the main stage of
sulphide mineralization, showing L + S + V phases, indicate a range of
temperatures between 211 and 339°C (average 275°C), and salinities between 30 and 43 wt% NaCl equivalent (mean 35 wt%
NaCl equivalent). Later stage fluid inclusions (L + S + V and L + V phases)
intergrowths twins in dolomite and quartz crystals, and last stage
sphalerite, indicate temperatures in the range 280–70°C and salinities between 23 and 38 wt% NaCl equivalent.

At Dikulshik, two fluids were identified by fluid inclusion analysis in
sphalerite, dolomite, quartz-harzite and calcite (Dewhurst et al., 2005;
Huet et al., 2007): (1) a high-salinity fluid (20.7–24.4 wt% CaCl₂ equivalent) inclusions with L + V phases (H₂O–CaCl₂–NaCl composition) indicating temperatures between 115 and 185°C, related to the first generation sulphides; (2) a second type fluid with lower salinities (254–1253 wt% NaCl equivalent; inclusions with L + V or
only L phases) and temperatures around 70°C, related to the late
dominantly clastic mineralization.
The stratiform Cu-Co deposits of the Roan Group in Congo and Zambia are marked by hydrothermal veins emplaced late in the evolution of the Lufilian Arc. At Museshi, Richards et al. (1988) recorded binodal populations in fluid inclusions from quartz (+ fissionation) veins similar to the 7n-Nb deposits. The U-Pb population is marked by values between 342 and 373 °C whereas the U-Pb population has temperatures ranging between 195 and 229 °C. The salinity is also higher in the U-Pb population (minimum 39 w.t.% NaCl = 15 w.t.% HCl) and lower in the U-Pb population (28 w.t.% NaCl = 17 w.t.% KCl). At Luwulwishi (in Congo) and Chimbinshi (in Zambia) the distribution of Th, U, and saillites of fluid inclusions in late stage veins and in the tectonic breccia cement are between 197 and 430 °C, while saillites are between 22 and 40.5 w.t.% NaCl equivalent (Anelli, 1988; Gregory et al., 2005; Diwade et al., 2006; El-Dessouky et al., 2006, 2008). These values are typically higher than those found in ultramafic and dolostone associated with the early diagenetic Co-Cu mineralization at Chimbinshi, Kamoto-Principal and Mucubal (Kolwezi area, Congo) recording primary saillites in the sediments (Frohlich, 1959; Ngongo, 1957; Audewald, 1982; Anelli, 1988; Gregory et al., 2005; El-Dessouky et al., 2008).

Fluid inclusion data for the Zn-Cu-Pb deposits and for veins or tectonic breccia in the stratiform Cu-Co deposits are summarized in Tables 6 and 7, and Th and saillite are plotted in Fig. 20. They are compared to data from Nanba Zn-Pb deposits (Berg Aukas, Tuamotu, South Spring) by those Th and saillite values in the range of 137-170 °C and 20-23 w.t.% NaCl equivalent, respectively (Chetty and Frey, 2000).

7 Isotope studies
7.1 Lead isotopes

In the past, a number of Pb isotopic analyses have been performed on sulphide deposits at the Roan Range in Zambia. The data are summarized in Table 8 and plotted on 206Pb/204Pb vs. 207Pb/204Pb and 208Pb/204Pb vs. 206Pb/204Pb diagrams (Fig. 21a, b). All sulphides from the Zn-Pb-Cu orebodies in Congo and in Zambia show small variations in their Th isotopic compositions within the following ranges: 206Pb/204Pb = 17.25-18.53; 207Pb/204Pb = 15.50-15.70; 208Pb/204Pb = 15.49-15.70.

Table 7: Chemical composition of Zn-Pb-Cu deposit (Kolwezi area, Zambia).

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Kamoto-Principal and Mucubal (Zambia)</th>
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<tbody>
<tr>
<td>High Th fluid inclusions in tectonic breccia</td>
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<td>Low Th fluid inclusions in orebody</td>
<td>38.4-41.5 °C</td>
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<tr>
<td>Salinites</td>
<td>35.3-41.5 °C</td>
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<tr>
<td>w.t.% NaCl</td>
<td>35.3-41.5 °C</td>
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<td>w.t.% NaCl</td>
<td>35.3-41.5 °C</td>
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<tr>
<td>Low Th fluid inclusions in orebody</td>
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<td>Salinites</td>
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<td>w.t.% NaCl</td>
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<td>Homogenization temperature (°C)</td>
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Ranges of the lead isotope ratios for sulphides from Zn-Pb-Cu deposits at Kupangi, Lombe, and Kenge (Walter et al., 1954, 1958), and for tectonic breccia from the Kupangi fault breccia (Walter et al., 1954).

[Fig. 20: Homogenization temperature and salinity from sphalerite, quartz, and dolomite associated with the mineralization from Kupangi, Kenge, and Kupangi-Fundu deposits. Composition of Kupangi deposit (Kolwezi area, Congo) and tectonic breccia in the Central African Copperbelt (Chambohi, Mucubal, and Luwulwishi). Comparison of ranges of lead isotope ratios for 7n-Nb deposits and in the Orange River Valley (E. and J. van der Haagen).]
Such restricted variations for Zn-Ph ore deposits at the southern margin of the Congo craton suggest that these deposits may have the same metal source, namely the upper continental crust.

Pyroclastic sulfides from the stratiform members of the Itabo Group (e.g., Kikuri, Kinshasa, and Muapisi; Table 8 Fig. 11c, d) are marked by significant variation in lead isotopic compositions, from low values similar to those documented in Zn-Ph deposits up to more radiometric composition: $^{206}Pb/^{204}Pb = 17.56-17.54$ and $^{207}Pb/^{204}Pb = 15.31-15.44$ and $^{208}Pb/^{204}Pb = 35.09-146.51$ (Richards et al., 1998b). Recent lithostratigraphic studies (Calheux et al., 1994, 1995) have shown that the main copper deposits are hosted by coeval lithostratigraphic units in Congo (Itabo Supergroup) and in Zambian (Kivu Formation) and it seems inevitable that the same differences could be attributed to the large variation of Pb isotopic composition within the stratiform Cu-Cos sulfides and between the stratiform Cu deposits and the stratiform Zn-Ph deposits. Thus, one must seek the major cause for heterogeneities in the lead sources.

The range of lead isotopes in the Paleoproterozoic calc-alkaline rocks in the Luapula/Cobre (Mufungo granodiorite) and in the Lungwesi block (Pepa Lufutuma) is relatively limited with $^{207}Pb/^{204}Pb = 17.36-20.73$, $^{206}Pb/^{204}Pb = 15.52-15.98$ and $^{208}Pb/^{204}Pb = 37.21-41.80$. Since lead isotope composition of these granites has evolved owing to U and Th radioactive decay, a correction must be applied before comparison with sulfide from the Namaqualand copper deposit. The calculations show that, at around 700 Ma, the lead isotope ratios of these calc-alkaline rocks were similar to that of the lead radiogenic sulfide in the stratiform copper deposits and that of the Zn-Ph ores, i.e., $^{206}Pb/^{204}Pb = 18.1$, $^{207}Pb/^{204}Pb = 15.5$, and $^{208}Pb/^{204}Pb = 37.3$.

Comparison of the Pb isotopic values from the Central Africa and Namibian Zn-Ph deposits suggests that the main metal source for these deposits is the upper continental crust.

Fig. 21. (a) $^{206}Pb/^{204}Pb$ vs. $^{207}Pb/^{204}Pb$ and (b) $^{206}Pb/^{204}Pb$ vs. $^{208}Pb/^{204}Pb$ diagrams for sulfides and host rocks from Zn-Ph-Cu deposits at Kipushi, Lumbe, and Kongere (Wainwen and Chinha 1984), Kibwezi and Tumbula (Kalsakau et al., 1998), Serra Do Ramalho (Barros et al., 1994), and Nova Redonde (Argentina) (Hagemann, 1984). Labeled points show the Pb isotopic compositions of sulfides and host rocks from Zn-Ph-Cu deposits at Kipushi, Lumbe, and Kongere (Wainwen and Chinha 1984), Kibwezi and Tumbula (Kalsakau et al., 1998), Serra Do Ramalho (Barros et al., 1994), and Nova Redonde (Argentina) (Hagemann, 1984), compared to those from the Central Africa and Namibian deposits.
sequences of the São Francisco Craton in Brazil shows that the Morro Agudo, Vazante, and Nova Redenção deposits (203Pb/206Pb = 17.81-19.57; 207Pb/206Pb = 13.59-15.34; and 208Pb/206Pb = 13.36-14.11; Mid et al., 2005) have similar isotopic ratios. In contrast, the other Zn-Pb deposits in Brazil (except Bauru) have different ranges of isotopic ratios (fig. 21c).}

7.2. Stable isotopes

Sulphur isotope variations, in terms of conventional permil deviation (δS ‰) relative to the Canyon Diablo Troilite (CDT), are shown in Table 6. The δ34S values for the Kipushi deposit show the greatest range: from -3.2‰ to +1.6‰ (Dechoy and Jensen, 1985) which is in marked contrast to the more homogeneous isotopic ratios of massive sulphides at Kifwebe (10.1 to -18.7‰) (Ramon and Freidrich, 2007). The Kifwebe deposit where the common host rocks are serpentinite and amphibolite in which the mineralization is dominantly in chromitite lenses and dolostones of the Kalulushi Formation, the main host rocks, have relatively heavy δ34S values from +12.8 to +19.2‰ (in average 15.6‰) (Dechoy and Jensen, 1985), in contrast subhedral in the sub-sedimentary dolostone and dolomite of the Kalulushi Formation have the largest spread from -2.8 to +18.0‰ (n = 9), whereas the barren dolomite shales of the Nguba rocks enriched by mineralized horizons have uniform and lighter δ34S values between -5.7 and +2.0‰ (n = 8, average -2.5 ± 2.8‰). (Dechoy and Jensen, 1985).

Isotopic ratios of sulphides from other Zn-Pb deposits for which data is available (Milibeg -10.1 to +14.0‰; and Kawa -11.3 to +15.4‰; Dechoy and Jensen, 1985) have δ34S values comparable to those found at Kifwebe. Such negative δ34S values with narrow spreads are characteristic for a sedimentary origin of the produced through bacterial reduction of seawater sulphate (Ramon and Freidrich, 2007). The negative δ34S values in the Kipushi deposit are probably from diagenetic alteration whereas the much heavier isotopic ratios of +15.1‰ in the Kilombele Formation are up to 10‰ higher in the main host rocks. These are the average isotopic ratio at +17.5‰ for Neoproterozoic seawater sulphate on the Copperbelt (Dechoy and Jensen, 1983; Clappo et al., 1983).

In comparison, the δ34S values of pyrogenous metamorphic rocks in the Dijana/ trial/lambombe subgroup in the Copperbelt range from -11.2 to +1.5‰ (Dechoy and Jensen, 1983). Sulphur isotope ratios in fresh basic rocks generally lower order variations from (around 0‰, the high fractionation (e.g. 15‰) and the high values of δ18O (e.g. 7.1‰) are typical of the large isotopic shifts caused by isotopic fractionation processes that are generally thought to preserve sulphur isotope compositions (Rye and others, 1974; Olmino, 1978; Oldio, 1986; Gower, 1984). It is therefore likely that the heavy δ34S values were assimilated from the country rocks during the intrusion of the gabbroic rocks at around 760 Ma. These country rocks are characterized by heavy sulphur isotopes δ18S = 17.5‰, whose ultimate source was seawater sulphate.

The δ34S for Cu sulphides from the stratiform Cu-Co deposits in the Copperbelt are very light (-8.7 to +11.0‰) of the Copperbelt (Cillers et al., 2005b and references therein). This wide spread of sulphur isotope ratios probably indicates involvement of different diagenetic sulphuric acid seawater sulphate in the ore-forming processes of these stratiform deposits.

Carbon and oxygen isotopes compositions are only available only for the Copperbelt where the mineral carbonates (Ramon and Freidrich, 2007), the δ13C and δ18O values in the Kalulushi dolomite show characteristic differences from those found in the Copperbelt (Lerouge et al., 2004; Rainaud et al., 2005a). In the case of Kipushi deposit, the NE-SW fault system probably represents reactivated basement faults (De Swardt et al., 1985). Both the NE-SW faults and the Kalulushi dolomites terminate at the younger Meikle fault (Ramon and Freidrich, 2007); whereas the 1/1 and 1/2 and 1/3) which is associated with sedimentary processes at 526 Ma in central Zambia (Barret et al., 1975).

According to Chau (1989) and Chau and Lambe (1971), the Kipushi deposit is characterized by mineral assemblage of the greenschist facies, including barite magnonite and (Ba, K)-feldspar of meta-sedimentary origin. The Kipushi deposit also experienced a phase of low grade metamorphism at 538 and 536 Ma in the Kalulushi Formation (Karamba and Freidrich, 2007). Metamorphism could have occurred.
9. Comparison with similar deposits/occurrences in Namibia and western Congo

9.1. Deposits in Namibia

More than 600 Cu-Pb-Zn-V deposits and occurrences have been listed in the Otavi Group in Namibia, lying on the southern margins of the Congo craton. Many of these are similar to the Zn-Pb deposits in the Central African Copperbelt. On the basis of regional associations (Kamona and Glesne, 2007; Hoffman et al., 2007; Kamona and Glesne, 2007), these deposits and occurrences are hosted in carbonate units of the Otavi Group that are stratigraphically equivalent to the Mutenhe Subgroup (e.g., the Zn-Pb-V Berg Aukas deposit in the Ahnab Subgroup) or to the Gobeha Subgroup rocks (e.g., the Cu-Pb-Zn-Khoab Spring, Ohuka, Zn-Khoab, and Zn-Khoab deposits in the Tsumeb Subgroup). In Table 9, the age of the Ahnab Subgroup, which contains typical Zn-Pb-V Mississippi Valley-type (MVT) deposits such as Berg Aukas and Ahnab West, hosted in carbonates of the Gauss and Augen formations, respectively (Kamona and Glesne, 2007 and references therein), is constrained between 746 ± 2 and 635 ± 12 Ma, which are the respective ages of the Chas and Ghash glaciations in Namibia (Hoffinan et al., 1998; Hoffman et al., 2004). The age of the Tsumeb Subgroup may be bracketed between 635 and 550 Ma, with the latter age being related to volcanics of the Kalkar and Congo sections (Lambrinz et al., 1991; Akram et al., 2001).

Mineralogically simple Zn-Pb-dominated ores comprising sphalerite, galena, pyrite, minor chalcopyrite, bournonite, and covellite, minerals such as Ag, Cd, Cu, Ga, Ge, and Sn (e.g., Tsumeb deposit), the sulfide assemblages in the latter ores are composed of variable amounts of galena, tetrahedrite-choctawite, sphalerite, chalcopyrite-enargite, bournonite, pyrite, minor germanite, enargite, bronzite, Cu-bearing covellite, and Mo-W sulfides (Lambard et al., 1995; Hageng 1987; Melcher et al., 2003). As shown in Table 2, ore from the Khoab Spring deposit has higher Cu-As-Sb-Sb contents than those from Kipushi and Kalowe. The major sulfides in the Khoab Spring deposit are tetrahedrite, followed by enargite, galena, sphalerite, and pyrite (Melcher et al., 2003). Sphalerite and pyrite dominate sulfide minerals in the Tsumeb deposit, followed by Zn-tetrahedrite, enargite, galena, pearsonite-polybasite, and Cu-bearing covellite. Paragenetically, the last-formed minerals are Cu-bearing sphalerite, chalcopyrite, and Ag-enargite.

Table 9: Lithostratigraphy of the Damara Supergroup (Kamona and Glesne, 2007) compared to the Kalahari Supergroup (Calitz et al., 2007), and stratigraphic position of the major deposits.

<table>
<thead>
<tr>
<th>Group</th>
<th>Formation</th>
<th>Deposit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mutenhe</td>
<td>Tschab</td>
<td>Tscha Co-(Ag)</td>
</tr>
<tr>
<td></td>
<td>Hunteine</td>
<td>Khoab Co-Pb-(Zn)</td>
</tr>
<tr>
<td></td>
<td>Landschock</td>
<td>Tsumeb Pb-Cu-Zn-(Ge)</td>
</tr>
<tr>
<td></td>
<td>Mieberg</td>
<td>Alredy V Khoab Springs Pb-Zn-Zn</td>
</tr>
<tr>
<td></td>
<td>Gobian (diamictite)</td>
<td>855 Ma</td>
</tr>
<tr>
<td>Ahnab Subgroup</td>
<td>Ahehe West Pb-Zn-V</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ahehe</td>
<td>635 Ma</td>
</tr>
<tr>
<td></td>
<td>Berg Aukas Pb-Zn-V</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Berg Aukas Varion (diamictite)</td>
<td>713 Ma</td>
</tr>
<tr>
<td>Frast</td>
<td>Asteroid</td>
<td>Athond Co; Abschilde-Cu</td>
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<td></td>
<td>Mares</td>
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</table>

The jasperitic orebody was the largest Pb-Cu-Zn deposit in the Otavi Mountain Land until its closure in 1985. The mineralization is confined to an epigenetic structure on the northern flank of a large syncline, cutting through the uppermost carbonate members of the Tsumeb Subgroup, and reaching a depth of 1400 m below surface. Sulfide ore is replaced by a chloritic sandstone representing the top of a karst-induced breccia pipe, and the host dolostone as manto ores. Due to complex hydrothermal conditions, sulfide ores have been oxidized to a great depth, producing specular secondary mineral specimens of Cu-As-Zn sulfates, carbonates, arsenates, nantates, and oxides and urites. The Pb isotope data for Tsumeb show an upper crustal origin for the ore lead, which is similar to isotopic crustal signatures of the Lufilian Arc (Kamona et al., 1995) and volcanic-associated deposits such as Rush Pinah and Skepios Zinc in the
Gariep Belt of Namibia (Finnemel et al. 2004). The Tsumeb deposit occurs in banded and highly fractured carbonate tufa and lies ca. 530 Ma age of mineralization (Kanana and Gümkel, 2007) is synerctic in relation to the second phase of the Kamara Orogeny that occurred between ca. 576 and 520 Ma (Klein 1982; Raasch and Martin; 1981; Raasch et al., 1983).

The fault plane in the southern part of the Otavi Mountain Land is hosted within the upper carbonate units of the Tsumeb subgroup, and consists of several vertical to subvertical fractures which terminate in contact with overlying slates. Massive to semi-massive sulfide ore is best developed in zones of brecciation within dolomite and associated feldspathic sandstone lenses. The ore consists of chalcopyrite, bornite, galena, chalcocite, minor sphalerite, arsenianite, tetrahedrite, and asbestiform sericite and talc. (Kanana and Gümkel 2007). The presence of intraformational Fe-Mn oxide/silicate beds within zones of tectonic transposition is a feature unique to the deposits in the Otavi Mountain Land.

9.2. Cu–Pb–Zn mineralization in the West-Congo foldbelt

The Neoarchean West Congolian Group in Bas-Congo is a sedimentary succession comparable to the Katangan Supergroup (Table 10) hosting several Pb-Zn deposits or occurrences (Cahen, 1954). The succession comprises ca. 6000 m thick per-Faceto-African paragneiss, pelitic phyllite, calciphylite and schistose sequence of the Sanikwia, Haut Shianga, and Schiste-Calcaire subgroups, and ca. 2000 m thick late pre-Faceto-African mafic sequence of the Mukupa and Iinki subgroups (Tack et al., 2001). The lowermost Sanikwia Subgroup unmetamorphically overlies a granitic basement. The base of the West Congolian sediments of the Calciphylite-Calcaire subgroups are marked by two regionally extensive diamictons named "Lower Mixture" (ca. 400 m thick) and "Upper Mixture" (ca. 150 m thick), respectively. The Lower Mixture represents the glaciogenic glacial event, while the Upper Mixture is of Maissian age (Posselet, 2007). The mafic sequence deposited is described by (Tack et al., 2001).

The Bamba-Mbena Cu-Pb-Zn deposit, 70 km south of Kiangwa, is the most documented in the area, it occurs over 3.5 km along a major E-W fault in contact with the Schiste-Calcaire, Mukupa and Iinki subgroups, and shows strong similarities with the Kupena deposit (Cahen 1954; Knudt-Flode, et al., 2002). Mineral occurrence assemblage ca. 150/600 tons metal Cu+Pb+Zn. The primary sulphide mineralization consists of impregnations and occasional massive lenses hosted in sillimanite breccias of the Mupika unit, and veins in hematite breccias of the Schiste-Calcaire; it occurs also in contact with biotite hornfelses. The Cu (mackinawite) occurs predominantly in the western part of the deposit, while Pb-Zn occurs (sphalerite-pyrite-galena) associated with Fe-Cu, and Fe-Cu-Co (as chalcopyrite-tetrahedrite) are characteristic of the eastern part. Cu is contained in sphalerite, and Ag in galena. A paragenetic study of the primary ores indicates that pyrite and sphalerite deposited in the early stage, while galena is the latest sulphide.

10. Discussion and genetic interpretations

Various hypotheses have been proposed to explain the origin of the mineralizing fluids that form the Zn-Pb-Cu deposits of the Copperbelt in Central Africa, including:

a) A magmatic hydrothermal origin related to deep-seated igneous intrusions for Kalwe (Taylo, 1954) and Kipushi (Thome, 1926; Tondeligne and Oesterbock, 1954; Wahwee and Chabu, 1994);
b) Basin degassing models involving (i) evolved connate fluids that leach metals from the sedimentary pile, including the early uplift sediments (Hartmann, 1971; Hughes et al., 1964), or (ii) tectonic brines expelled during orogenesis (Dunne and Seggerson, 1995; Kanana et al., 1995; Kanana and Fricchino, 2007), or (iii) fluids produced by metasomatic decay-watering (Uring, 1988, 1999);
c) The dissolution of a salt diapir for the Kupena deposit (De Magne and Pommier, 1999);
d) Concomitant lead formation and mineralization pre-dating orogenesis for Kipushi (Chabu, 1965) and Kalwe (Sanana et al., 1988; Sweeney and Bickel, 1988);
e) Remobilization of pyrometamorphic and protmetamorphic ores for Kalwe (Takken and Fricchino, 1990).

The petrology of these hypotheses may be attributed to differences in time, and the timing of the mineralization in relation to rifting, sedimentation, tectonic uplift, and orogeny. The sequence that occurred in the basaltic sequence, is exposed at the surface and is garnetized for the metals of sulphur and pyrite, and by different mechanisms of sulphide deposition. Here, the data are critically assessed in order to propose a genetic interpretation which satisfies all available constraints.

10.1. Geological characteristics of the deposits

Most Zn-Pb-Cu deposits in Congo are hosted in the same lithostratigraphic carbonate sequence at the bottom of the Nguva Group, characterized by chaledony and marl carbonates. According to the zonal deposits, occurrence of a Precambrian sediments, consisting of impregnations and occasional massive lenses hosted in sillimanite breccias of the Mupika unit, and veins in hematite breccias of the Schiste-Calcaire; it occurs also in contact with biotite hornfelses. The Cu (mackinawite) occurs predominantly in the western part of the deposit, while Pb-Zn occurs (sphalerite-pyrite-galena) associated with Fe-Cu, and Fe-Cu-Co (as chalcopyrite-tetrahedrite) are characteristic of the eastern part. Cu is contained in sphalerite, and Ag in galena. A paragenetic study of the primary ores indicates that pyrite and sphalerite deposited in the early stage, while galena is the latest sulphide.

<table>
<thead>
<tr>
<th>Table 10</th>
<th>Lithostratigraphy of the West Congolian Group (Tack et al., 2001) compared to the simplified Kanana succession, and stratigraphic position of the Bamba-Mbena and Kipushi deposits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group</td>
<td>Supergroup</td>
</tr>
<tr>
<td>----------</td>
<td>------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>West Congolian</td>
<td></td>
</tr>
<tr>
<td>Mukupa</td>
<td>Cu-Pb-Zn</td>
</tr>
<tr>
<td>Schisto-Calcaire</td>
<td></td>
</tr>
<tr>
<td>Upper Mixture (diamictite)</td>
<td></td>
</tr>
<tr>
<td>Haut Shianga</td>
<td></td>
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<tr>
<td>Lower Mixture (diamictite)</td>
<td></td>
</tr>
<tr>
<td>Sanikwia</td>
<td></td>
</tr>
<tr>
<td>Lower Ditomate</td>
<td></td>
</tr>
<tr>
<td>Kupena</td>
<td></td>
</tr>
<tr>
<td>Mupika</td>
<td></td>
</tr>
<tr>
<td>Schisto-Calcaire</td>
<td></td>
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<tr>
<td>Upper Mixture (diamictite)</td>
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<td>Haut Shianga</td>
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</tr>
<tr>
<td>Sanikwia</td>
<td></td>
</tr>
<tr>
<td>Lower Ditomate</td>
<td></td>
</tr>
</tbody>
</table>

517 Ma
sequence shows strong similarities as the host rocks in Congo, with the difference of a stronger metamorphic overprint in Zambia compared to Congo (François and Calvert, 1938). Dilek is an exception to this rule, being hosted in sandstones and sandstone breccias from the upper part of the Kundelungu sequence.

All deposits, in both Congo and Zambia, display strong structural control. The mineralization was deposited as massive bodies, mostly in the carbonates by dissolution of the host rocks, and is linked to faults developed during the second (D₂) deformation event of the Luš envision.

The primary Zn-Pb mineralization consists of sulfides and is locally associated with significant concentrations of Cu (e.g., at Kipushi in Congo, at Mukushi and Lukushi in Zambia). Zn-Pb represents the most important commodity. Schaltinite, Chalcocite, Bornite, Chalcopyrite, and Galena are the main minerals associated. Galena and sphalerite are the main mineral associations. Minor Cd, Cu, Ge, Ag, Bi, As, Mo, and Au occur at Kipushi, while minor V, Ag, Cd, Cu occur at Kabwe, and only minor V at Arfvedson, Carman, and Chishanda in Zambia. By contrast, the Dilek deposit in Congo contains mainly Cu besides minor Zn, Pb, Ag, and As, and Kansanshi in Zambia only Cu and As.

No contemporaneous igneous rocks are directly associated with the deposits. The most important igneous events on the Copperbelt are indicated by the widespread emplacement of mafic bodies at ca. 765–735 Ma (Armstrong et al., 1999; Key et al., 2001; Barron et al., 2003) in the Rippons/Kitshimasho and Kasanka sedimentary rocks, while hydrothermal events affected the stratiform Cu-Co ores between 663 and 515 Ma (Richards et al., 1984a,b; Kampanu and Calvert, 1998; Larsen et al., 2004; Ruhoo et al., 2005b). According to John et al. (2004), geochemical data obtained from conicoidites and gabbros in central Zambia provide evidence that they formed at an upper mantle spreading event and that they are relics of a slab subduction of Neoarchean oceanic crust. The age of the mafic granitoid bodies in the Luš envision is indicated by the spreading event, and the subduction event is significantly younger than the recently obtained ~450 Ma age of the Kipushi Zn–Cu–Pb ore.

As suggested by Kamana et al. (1999), a candidate for the youngest igneous event that could be related to mineralization at Kipushi is the post-metamorphic hydrous symplectite intrusions in the Domes area south of Kipushi, for which 40Ar/39Ar ages of 450 to 417 Ma have been obtained (Cosi et al., 1992). Other Katangan granitic igneous rocks (such as the Hooz massif) are allipated toward the north of the Domes area, from which three 40Ar/39Ar ages of 570–530 Ma (Hanson et al., 1993), and thus older than the Kipushi deposit and about 100 Ma younger than the Dilek deposit.

**1.2. Age of Zn–Pb mineralization**

The 210 Pb My age difference between Kabwe (860 Ma) and Kipushi (440 Ma) suggests that the two major mineralizing events are responsible for the main Pb-Zn mineralization in the Luš envision. The 680 Ma event may be correlated with a reverse-facies event associated with high fluid circulation during the collision phase of the Luš envision. The 450 Ma event is slightly more recent. Therefore, the two major Pb-Zn deposits of Kabwe and Kipushi probably represent epigenetic and post-tectonic types of mineralization, respectively.

Another ore-forming event is indicated by the 544 ± 2 Ma and 532 ± 2 Ma Re-Os age of Cu–Au vein mineralization at Kansanshi (Tennakley et al., 2000) and by a 518 ± 2 Ma hydrothermal event recognized at Musushi (Richards et al., 1984a,b). The 514 Ma event probably represents an early post-metamorphic ore-forming event as indicated by the 512 Ma cooling ages in micas (Cosi et al., 1992; John et al., 2004) and by the occurrence of two stages in the Luš envision.

**6.1. Ore fluid composition and temperature of deposition**

Fluid inclusions studies indicate at least two stages of mineralization at the Kipushi (Cu–Pb–Zn–Cu–Pb–Zn–Pb–Ag) deposits. The first stage is characterized by ore fluids with high temperature and salinity, which have comparable values with those observed at the stratiform Cu-Co deposits in Congo (e.g., Musho and Liwisch; Fig. 28). The high salinity of these fluids may be due to extensive evaporation of seawater dissolution of Ross Group evaporites or mixing between these end-member water types (Hanan, 1995).

For the second stage, marked by lower temperature and salinity, is characterized by values comparable to those of the Bong-Akans and Tunehe deposits, and falls in the range of type-2 Zn–Pb deposits (Muli et al., 2005). The decrease in salinity with decreasing temperature shown by these secondary fluid inclusion populations could result from mixing of low-salinity with low-temperature (liquid–liquid) solutions associated with the thrust tectonics of the Luš envision (Calvert and Kampanu, 1995), and/or mixing with meteoric water for Kabwe (Kamana and Friedrich, 2007), or from a simple cooling with depletion of KCl (Richards et al., 1984a,b).

**1.3. Source of metals**

The homogeneous lead isotope ratios of galena from Kabwe (Kamana et al., 2000) support the presence of upper crustal sources rocks with relatively high 206Pb/204Pb (18.31) and 207Pb/204Pb (15.08) ratios compared to the Kipushi deposit which has lower 206Pb/204Pb (13.44) and 207Pb/204Pb (15.31) ratios more typical of conformable massive sulphide deposits (Stacey and Krane, 1975; Walkveen and Shalek, 1981) and Kamana et al. (2000). An interpretation of the lead isotope ratios for the Kipushi deposit as indicating a significant mantle component in the isotopic composition of the Kipushi ore lead, however, the recent lead isotope data of Schneidler et al. (2007) combined with initial lead isotope data of Cosi et al. (1992), indicate significant crustal contributions.

**1.5. Source of sulfur**

The ore deposits are associated with rocks showing evaparitic conditions, suggesting a marine origin for the sulfur. The negative and homogenous sulphur isotope ratio of ore sulphides (−18 to −12.3‰) from Kabwe (Kamana and Friedrich, 2007) are typical of sedimentary sulphates produced through bacterial reduction of seawater sulphate and, ultimately, a sedimentary source for the sulphur. Other Zn–Pb ore zones with similar sulphur isotope ratios (Douwe and Jensen, 1985) to Kabwe include Rossa (Fig. 2) and Muborg (Fig. 18). The sulphur isotope ratios for Kipushi sulphides show a wide range from heavy (−19.2 to −1.0‰) to light (−2.6 to 18.0‰) values (Douwe and Jensen, 1985) with sulphides from the Kabwe mine being heavier and more homogenous (+18.3 to +15.2‰) compared to those from the shale of the Kafue/Salile Fracture Formation (−2.6 to +18.0‰). The heavy isotope ratios from the Kabwe mine are close to the average value of +17.5‰ for Neoarchean evaporitic sulphate on the Copperbelt (Dowek and Jensen, 1985; Clapston et al., 1988). A seawater sulphate source is therefore suggested for the Kipushi deposit.
The Pb-Zn deposits in the Lufilian Arc are similar to Mississippi Valley-type (MVT) deposits, which are typically stratiform, epigenetic orebodies that occur in carbonates or evaporites, and are characterized by the absence of vein-like structures. These deposits are often associated with carbonate-rich (SEDEX) deposits, which are characterized by the absence of massive sulphide deposits and the presence of disseminated sulphides. The SEDEX deposits are usually associated with stratigraphic traps and are often stratiform in nature. They are also characterized by the absence of significant hydrothermal alteration.

The SEDEX deposits often occur in the form of lens-shaped bodies of massive sulphides, often with a central core of massive sulphides and a peripheral zone of disseminated sulphides. These deposits are typically associated with evaporite or carbonate-hosted environments and are often associated with stratigraphic traps, such as those found in the Lufilian Arc.

In the Lufilian Arc, the SEDEX deposits are typically associated with stratigraphic traps, such as those found in the Lufilian Arc. These deposits are often associated with evaporite or carbonate-hosted environments and are typically lens-shaped bodies of massive sulphides, often with a central core of massive sulphides and a peripheral zone of disseminated sulphides. These deposits are typically associated with stratigraphic traps, such as those found in the Lufilian Arc.

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Generally Mt. brines are rich in Ba and F. The fluids at Kipsigis contained both elements as indicated by neofomed F-rich phlegmopites in the ores, kambasparitization of Bemiga's, F-rich mica schistose and barites. In addition, Ba-Fe veins (barite-barite) of carbonate to marbles are known in the Kajabe fault (e.g., the Kainoi and Kamboe-Kaolite area, Fig. 3), associated with faults developed during the second (Ithi) to date (strata) over recent orogenesis of the basement and rocks extending across the Kaidungu, Nguku and Riao (Murang'a, Kilgoris) successions (Miaou, 1984; Ismaele and Miaou, 1997).

Although these veins remain poorly documented, the current data suggests that they are also part of the Mt. mining event that produced Zn-Pb-Cu deposits in the Central African Copperbelt.

11. Observations

The Lufilian Arc of the Central African Copperbelt is a complex metallogenic province containing stratiform-sediment-hosted Cu-(Co-(Cu)) deposit, largely syngeneic to syngeneic origin as well as stratified-Cu-(Cu) deposit. It is characterized by a syngeneic origin and post-tectonic hydrothermal vein-type-(Cu) deposit. The geotectonic evolution of the Lufilian Arc is related to breakup and subsequent amalgamation of the Rodinia and Gondwana supercontinents, respectively during a Wilson cycle that involved continental rifting, spreading subduction and eventual continental collision from ca. 800 to 512 Ma.

The Zn-Pb-(Cu) deposit of the Lufilian Arc formed from basinal brines during two major mining events that characterized the stratiform deposits (e.g., Edoke) and post-tectonic deposits (Fig. Kipsigis). These deposits exhibit many of the geologic characteristics of Mississippi Valley-type deposit systems, including their clastic stratigraphic, epigenetic nature and occurrence in clusters within pelite or paleoplains of various ages.

The main ore-forming fluids were saline with moderate to high temperatures and could have been produced by normal geothermal gradients during basin evolution. Ore deposition occurred in carbonate rocks with favourable permeable structures including faults, veins, breccias and hydrothermal alteration at a rate of cooling, fluid mixing, pH change or addition of H₂S.

More data is required to better constrain the timing of the ore realization, but current data suggests that the stratified-Cu-(Cu) deposit of the Lufilian Arc formed over a time period spanning 250 Ma and included both syngeneic and post-tectonic types in relation to the Lufilian Orogeny. The polymeric nature, fluid inclusion characteristics, textural features, structural control and stratigraphic positions of the deposits are comparable to deposits found in the deformed Neogene-Ngwe-West-Congolan (e.g., Bambasikor) and Damaran belts (e.g., Tumse, Kombai and Rang Aka) as well as some Pb-Zn deposits in Brazil (e.g., Moro Agudo, Vazante, Noroeste mine).

Acknowledgements

This work was originally conceived and drafted by the late Professor Henri di Baix Kamanzi. The co-authors have, as far as possible, preserved Henri's genetic interpretations of the carbonate-hosted deposits described in this paper. The Google Earth Mining Company is thanked for its significant support in providing the necessary data (strata and in situ carbonates) used in the UNESCO/ICSG ICP 450 Project on sediment-hosted base metal sulfide deposits.

References


