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

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A B S T R A C T

Stratabound epigenetic sulphide Zn–Pb–Cu ore deposits of 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 minor Cd, Co, Ge, Ag, Re, As, Mo, Ga, 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 Kabwe in the Democratic Republic of the Congo and Zambia, respectively, are the major examples of carbonate-hosted Zn–Pb–Cu mined deposits with important by-products of Ge, Cd, Ag and V in the Lufilian 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 (680 to 450 Ma). The formation of the relatively older Neoproterozoic deposits is probably related to early collision events during the Lufilian 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 tectonogenesis. Ore fluid migration occurred mainly along major thrust zones and other structural discontinuities such as karsts, 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
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1. Introduction

The arcuate shaped Lufilian 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, Kaoko, Gariep and Saldania Belts) of southern Africa, linked by a third transcontinental orogen comprising the Damara Belt, the Lufilian Arc and the Zambezi Belt (Fig. 1). The transcurrent Mwembeshi Dislocation Zone (Fig. 1) separates the Lufilian Arc from the Zambezi Belt (Unrug, 1983). Geophysical data (Eberle et al., 1995, 1996; Corner, 2000) indicates that the Lufilian 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 successions in the associated Neoproterozoic to Lower Palaeozoic basins (Fig. 1) spans over a period of 500 million years, starting with within-plate magmatism and rifting from ca. 1000 to 700 Ma, and culminating with collisional orogenesis at ca. 575 to 505 Ma (Hanson, 2003).

A number of epigenetic Zn–Pb–Cu massive sulphide deposits, including the major deposits of Kipushi and Kabwe, are hosted in deformed platform carbonates of the Lufilian Arc. Most of these deposits are relatively small, typically with only a few thousand tons of ore, including Kengere and Lombe in the Democratic Republic of Congo (DRC; hereafter Congo) as well as Bob Zinc, Lukusashi, Millberg, Mufukushi, Sebembere 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 Kabwe deposits are exceptionally large, with millions of tons of predominantly massive sulphide ore contained within stratigraphically extensive pipe-like bodies surrounded by silicified dolomite.

These carbonate-hosted deposits are of special interest since they are polymetallic (Zn–Pb–Cu–V–Cd–Ag), and also contain minor amounts or traces of Ge and Ga. 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 mineralization processes related to the genesis of these deposits have not yet been described holistically and, furthermore, their relationship

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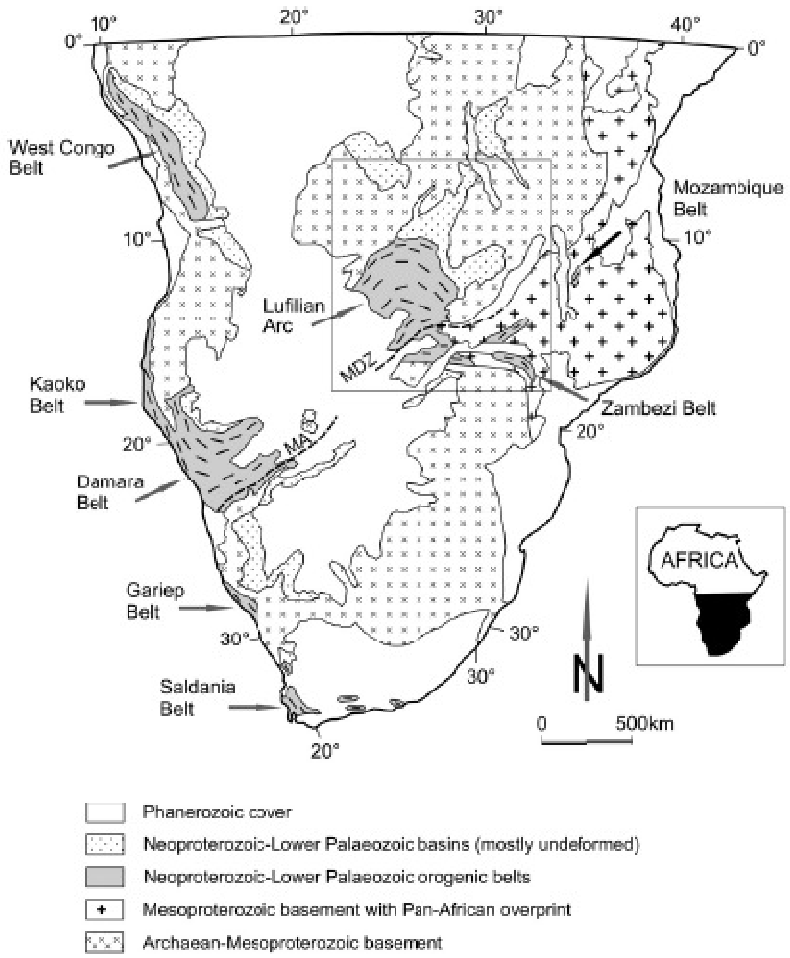

Fig. 1. Location of major Neoproterozoic orogenic belts and basins in the Precambrian tectonic framework of southern Africa (modified after Hanson, 2003). MA = matchless amphibolite; MDZ = Mwembeshi dislocation zone. The rectangle shows the position of Fig. 2.

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.

2. Geological background

The Lufilian Arc (Fig. 1) of the Central African Copperbelt is a northward-convex Pan-African orogenic belt consisting of Neoproterozoic metasedimentary rocks of the Katanga Supergroup (Mendelsohn, 1961a; Binda and Mulgrew, 1974; Unrug, 1983; Cailteux et al., 1994, 1995). Basement rocks underlying the Katanga Supergroup include Neoarchaean granites and granulites of the Congo Craton in the western part of the Lufilian Arc (Key et al., 2001) and Palaeoproterozoic schists, granites and gneisses of the Domes Region (Key et al., 2001; John et al., 2004), the external fold and thrust belt of the Lufubu Metamorphic Complex (LMC) on the Copperbelt (Mendelsohn, 1961b; Ngoyi et al., 1991; Rainaud et al., 2005a) and the quartzite–metapelite succession of the Muva/Kibaran Supergroup (Garlick, 1961; De Waele et al., 2006; Kokonyangi et al., 2006).

According to Key et al. (2001), the Neoarchaean Congo Craton (2523–2538 Ma) was affected by a 2560 Ma tectonothermal event when migmatites and associated granites were generated. Rainaud et al. (2005a) have interpreted the Palaeoproterozoic (2073–1874 Ma) LMC as a regionally extensive magmatic arc terrane which collided with the Tanzanian craton during the ca. 2050–1850 Ma Ubendian orogeny. The Muva/Kibaran Supergroup was deposited between ca. 1850 and 1650 Ma (De Waele et al., 2006; Kokonyangi et al., 2006) and

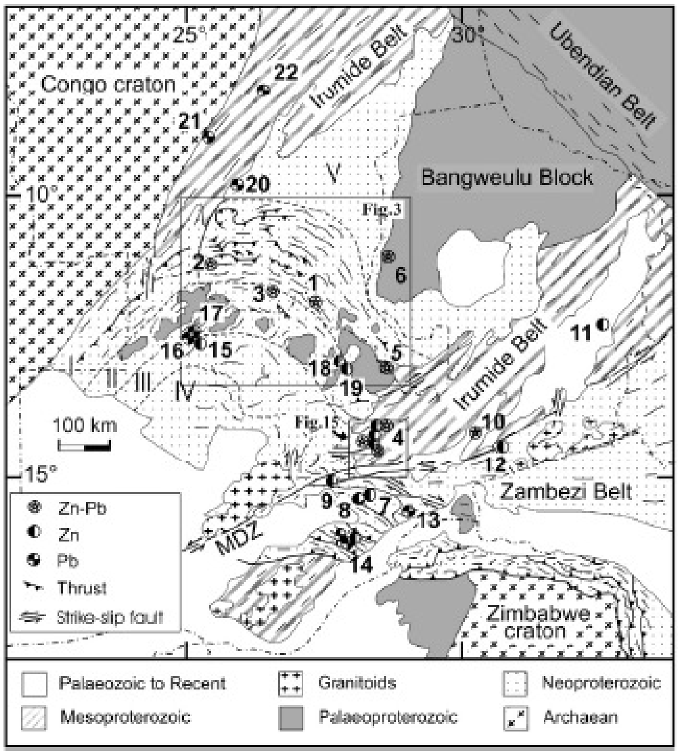

Fig. 2. Location of Zn–Pb deposits and prospects in the geotectonic framework of central Africa. 1. Kipushi, 2. Kengere, 3. Lombe, 4. Kabwe cluster (including Millberg, Mufukushi, Sebembere), 5. Itawa, 6. Bukanda, 7. Star Zinc, 8. Excelsior, 9. Bob Zinc, 10. Lukusashi, and 11. to 22. unnamed occurrences. I. External fold and thrust belt, II. Domes region, III. Synclinorial belt, IV. Katanga high, and V. Kundelungu aulacogen or palaeograben. Structural and tectonic domains based on data from the Geological Survey of Zambia (1981), Unrug (1983), Porada (1989), Ngoyi et al. (1991), Hanson et al. (1993), Hanson and Dumont (1997), Key et al. (2001), Rainaud et al. (2005a) and De Waele et al. (2006). Deposit locations based on data from Reeve (1963), Dechow and Jensen (1965), Kamona (1993), François 1974, and the Commission for the Geological Map of the World (2001).

was involved in a full Wilson cycle of rifting, ocean opening and closure, followed by subduction and collision (Kampunzu et al., 1986; Rumvegeri, 1991; Kokonyangi et al., 2006) which culminated in the assembly of the Rodinia supercontinent (Dalziel et al., 2000) during the Mesoproterozoic Irumide/Kibaran orogeny at ca. 1050–1020 Ma (Schenk and Appel, 2002; De Waele et al., 2006).

Intrusion of the Nchanga Granite at 883 ± 10 Ma (U–Pb on zircon; Armstrong et al., 2005) represents the youngest pre-Katangan igneous activity that affected basement rocks in the Central African Copperbelt (Garlick and Brummer, 1951).

2.1. *The Katanga Supergroup*

The Katanga Supergroup is commonly subdivided into three lithostratigraphic groups (Table 1): the basal Roan, the middle Nguba (formerly Lower Kundelungu) and the Kundelungu (formerly Upper Kundelungu) at the top (François, 1973b, 1987, 1995; Cailteux, 2003; Batumike et al., 2007).

The Roan Group in Zambia consists of a basal siliciclastic unit (Mindola Subgroup), a middle carbonate and siliciclastic unit (Kitwe Subgroup) and an uppermost carbonate unit (Kirilabombwe Subgroup). According to detailed correlations of the Roan Group sedimentary rocks between Congo and Zambia performed by Cailteux et al. (1994, 1995), these units correspond to the R.A.T ("Roches Argilo-Talqueuses"), Mines and Dipeta subgroups, respectively in Congo. The Mwashya Subgroup is regarded as the top of the Roan Group (Mendelsohn, 1961b; Fleischer et al., 1976; François, 1973b, 1987; Binda, 1994; Cailteux, 1994; Cailteux et al., 2005a, 2007). Other workers, however, consider the Mwashya as either a separate Group above the Roan (e.g., Porada and Berhorst, 2000) or as a subgroup at the base of the Nguba Group (e.g., Wendorff, 2003).

The Nguba Group is subdivided into two major units: the mixed carbonate–siliciclastic Muombe and the predominantly siliciclastic with minor carbonate Bunkeya subgroups, respectively (Batumike et al., 2007). Its base is marked by regionally extensive matrix-supported glaciogenic conglomerates of the Mwale Formation, widely known as the "Grand Conglomérat" (Van Doorninck, 1928; Gray, 1930; Dumont, 1971; Binda and Van Eden, 1972; François, 1973b; Cahen, 1978; Batumike et al., 2007). Cap-carbonates (Kaponda, Kakontwe and Kipushi Formations) overlying the Mwale Formation commonly contain Zn–Pb–(Cu) ore deposits in Congo (François, 1973a, 1974; Intiomale and Oosterbosch, 1974; Buffard, 1978, 1988; Intiomale, 1982; Batumike et al., 2007; Cailteux, 1989). Deposition of the Nguba Group is marked by a general north to south increase in thickness coupled with increasing carbonate deposition and decreasing grain size in siliciclastic rocks southward. Such trends suggest a proximal facies in

Table 1
Lithostratigraphy of the Katangan Supergroup in Congo and Zambia (modified from François, 1973b, 1987, 1995; Kampunzu and Cailteux, 1999; Cailteux et al., 1994, 2007; Cailteux, 2003; and Batumike et al., 2007).

Supergroup	Age	Group	Sub-group	Formation	Lithology
Katangan	< 573 Ma	Kundelungu (formerly Upper Kundelungu) Ku	Biano - Ku 3		arkoses, conglomerates, argillaceous sandstones
			Ngule Ku 2	Sampwe	dolomitic pelites, argillaceous to sandy siltstones
				Kiubo	dolomitic sandstones, siltstones and pelites
				Mongwe	dolomitic pelites, siltstones and sandstones
			Gombela Ku 1	Lubudi	pink oolitic limestone and sandy carbonate beds
				Kanianga	carbonate siltstones and shales
				Lusele	pink to grey micritic dolomite
	(± 635 Ma)			Kyandamu	Petit Conglomérat (glacial diamictite)
		Nguba (formerly Lower Kundelungu) Ng	Bunkeya Ng 2	Monwezi	dolomitic sandstones, siltstones and pelites
				Katete	dolomitic sandstones, siltstones and shales in northern areas; alternating shale and dolomite beds ("Série Récurrente") in southern areas
			Muombe Ng 1	Kipushi	dolomite with dolomitic shale beds in southern areas
				Kakontwe	carbonates
				Kaponda	carbonate shales and siltstones; "Dolomie Tigrée" at the base
	Congo ± 730 Ma			Mwale	Grand Conglomérat (glacial diamictite)

Supergroup	Age	Group (Congo)	Sub-group (Congo)	Formation (Congo)	Lithology (Congo)	Lithology (Zambia)	Formation (Zambia)	Sub-group (Zambia)
Katangan		Roan R	Mwashya (formerly Upper Mwashya) R 4	Kanzadi	sandstones or alternating siltstones and shales	dolomitic shales, grey to black carbonaceous shales, quartzites		Mwashia
				Kafubu	carbonaceous shales			
				Kamoya	dolomitic shales, siltstones, sandstones, including conglomeratic beds and cherts in variable position			
			Dipeta R 3	Kansuki R 3.4	(formerly Lower Mwashya): dolomites including volcaniclastic beds (765–735 Ma)	dolomites to arenitic dolomites interbedded with dolomitic shales; intrusive gabbros (formerly Carbonate Unit or Upper Roan)	Bancroft Kanwangungu RU 1 & RU 2	Kirilabombwe
				Mofya - R 3.3	dolomites, arenitic dolomites, dolomitic siltstones			
				R 3.2	argillaceous dolomitic siltstones with interbedded sandstone or white dolomite; intrusive gabbros			
				R.G.S. - R 3.1	argillaceous dolomitic siltstones ("Roches Gréso-Schisteuses")	shales with grit (Antelope Clastics)	Kibalongo RL 3	
			Mines R 2	Kambove R 2.3	stromatolitic massive, laminated, shaly or talcose dolomites; locally sandstone at the base; interbedded siltstones in the upper part	dolomite, argillite beds at top	Chingola RL 4	Kitwe
				Dolomitic shales R 2.2	R 2.2.2 & 3: dolomitic shales containing carbonaceous horizons; occasional dolomite or arkose	arkoses, sandy to dolomitic argillites	Pelito-arkosic RL 5	
					R 2.2.1: arenitic dolomite at the top and dolomitic shale at the base; pseudomorphs after evaporite nodules and concretions	arenites, argillaceous dolomites, argillites, dolomites, evaporites	Ore Shale RL 6	
				Kamoto R 2.1	stromatolitic dolomite (R.S.C.), silicified/arenitic dolomites (R.S.F./D.Strat.), grey argillaceous dolomitic siltstone at the base (Grey R.A.T.); pseudomorphs after evaporites at the contact with R.A.T.			
			R.A.T. R 1	red argillaceous dolomitic siltstones, sandstones and pelites ("Roches Argilo-Talqueuses")		conglomerates, coarse arkoses and argillaceous siltstones	Mutonda	Mindola RL 7
				base of the R.A.T. sequence - unknown		quartzites	Kafufya	
	± 880 Ma	basal pebble and cobble conglomerate				pebble and cobble conglomerate	Chimfunsi	
± 2050 Ma		Kibaran and pre-Kibaran						

R, Ng, and Ku are the codes for Roan, Nguba, and Kundelungu Groups, respectively. RL and RU are codes for Lower Roan and Upper Roan, respectively, in Zambia.

the north and a basin open to the south (François, 1987; Batumike et al., 2007).

The uppermost Kundelungu Group is subdivided into three subgroups (Gombela, Ngule and Biano) in Congo (Batumike et al., 2007). The Gombela Subgroup consists mainly of siltstone–shale–carbonate units, and is marked by the basal glaciogenic Petit Conglomérat (Kyandamu Formation) overlain by a cap carbonate (Lusele Formation). The Ngule Subgroup is a sequence of pelites, siltstones and sandstones, whereas the Biano Subgroup is an arenaceous unit of conglomerate, arkose and sandstone.

2.2. Tectonic evolution of the Katanga Supergroup

Initial continental rifting and sedimentation began soon after 880 Ma as indicated by U–Pb zircon ages from the Nchanga Granite (Armstrong et al., 2005) which is nonconformably overlain by basal conglomerate and arkose of the Mindola Subroup. U–Pb SHRIMP dating of detrital zircons from the arkose (Armstrong et al., 2005) has revealed that both the Palaeoproterozoic LMC (2081 ± 28 to 1836 ± 26 Ma) and the Nchanga Granite (880 ± 10 Ma) provided detritus to the lower units of the Roan Group (Armstrong et al., 2005; Master et al., 2005). Continental rifting on the southern edge of the Congo Craton resulted in the formation of a passive margin (Buffard, 1988; Porada, 1989; Porada and Berhorst, 2000; Key et al., 2001) where basal Roan Group continental fluviatile red beds and siltstones were deposited. The continental siliciclastic sediments graded laterally into shales, carbonates, evaporites and iron formations in a transitional peritidal and lacustrine environment (lagoon basin) and then to the carbonate-dominated platform of the Kirilabombwe/Dipeta subgroups which accumulated in a shelf environment (Cosi et al., 1992; Cailteux, 1994; Porada and Berhorst, 2000; Key et al., 2001). Volcaniclastics and banded iron formations developed in a deep rift basin environment characterized by extension-related mafic plutonism and volcanism (Kampunzu et al., 1991, 1993, 2000).

The intracontinental rift developed in response to tectonic stresses associated with the breakup of the Rodinia Supercontinent (Rogers et al., 1995; Unrug, 1996; Weil et al., 1998) due to upwelling of asthenospheric mantle that resulted in the generation of tholeiitic mafic magmas (Tembo et al., 1999). The intracontinental rift stage evolved into the proto-oceanic rift stage from ca. 765 to 735 Ma (Key et al., 2001; Barron et al., 2003) when oceanic crust was formed from extension-related intrusion of tholeiitic mafic dykes and sills and extrusion of mafic to felsic lavas and tuffs (Kampunzu et al., 1991, 1993, 2000; Meert and Van der Voo, 1997; John et al., 2003) which occur mainly in the Kirilabombwe/Dipeta, Kansuki (formerly Lower Mwashya) and Muombe sequences (Table 1) (Lefebvre, 1973, 1975; Cailteux, 1994; Tembo et al., 1999; Key et al., 2001; Barron et al., 2003; Kabengele et al., 2003; Kampunzu et al., 2003; Cailteux et al., 2007). During a major phase of extensional tectonics and normal faulting marking the transition of the continental rift to the proto-oceanic rift basin (Kampunzu et al., 1991, 1993) the ocean basin widened to >1000 km (John et al., 2003) with siliciclastic units of the Mwashya Subgroup (Cailteux et al., 2007) and of the overlying Nguba and Kundelungu Groups deposition.

Both the Grand Conglomérat and the Petit Conglomérat, which occur at the base of the Nguba and Kundelungu Groups (Table 1), are glaciogenic diamictites which may be correlated to the global Sturtian (ca. 730 Ma) and the Marinoan (ca. 635 Ma) glaciations, respectively (e.g., Hoffman et al., 1998; Fanning and Link, 2004; Hoffmann et al., 2004). The Sturtian age of the first glaciation event is postdated by the U–Pb zircon age of 735 Ma ± 5 Ma (Key et al., 2001) of interstratified mafic volcanics at the base of the Grand Conglomérat. No age data is available for the younger glaciation event represented by the Petit Conglomérat.

Extension was followed by convergence of the Congo and Kalahari Cratons, leading to subduction of oceanic lithosphere and eclogite formation at around 638 ± 61 to 595 ± 10 Ma (Sm–Nd garnet–whole rock ages; John et al., 2003). Lerouge et al. (2004) have determined U–Th–Pb ages of 709 ± 48, 603 ± 31 and 594 ± 8 Ma on monazite grains from the Luiswishi Cu–Co–U deposit in Congo which are within the error range of eclogite formation at 638 and 600 Ma. The 709 Ma monazite age is also consistent with the 744 ± 8 Ma Rb–Sr muscovite age of Cosi et al. (1992) for peak metamorphism in the Domes 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; Cahen et al., 1984; Cosi et al., 1992; Kampunzu and Cailteux, 1999) which resulted in the formation of thrust surfaces, nappes, and eclogite at depth (Cahen, 1970; Cosi et al., 1992; John et al., 2003). According to Cailteux and Kampunzu (1995), tectonic megabreccias at the base of the thrusted nappes also formed during this phase, facilitated by dewatering and fluidization of evaporitic material in the R.A.T. and Dipeta subgroups.

Continent–continent collision between the Congo and Kalahari Cratons occurred at ca. 530 Ma when talc–kyanite schists (whiteschists) formed under high pressure amphibolite facies conditions (John et al., 2004). The 529 ± 2 Ma $^{207}Pb/^{235}U$ monazite age of John et al. (2004) for the peak stage of metamorphism is also consistent with the 530 ± 1 Ma U–Pb age of recrystallized uraninite from Luiswishi (Loris et al., 1997). Continental collision at ca. 530 Ma corresponds to the Monwezian phase of the Lufilian Orogeny (Demesmaeker et al., 1963; Kampunzu and Cailteux, 1999), which resulted in northwest- and northeast-directed thrusting in the western and eastern arms of the Lufilian Arc, respectively (Key et al., 2001), as well as the formation of whiteschists, duplication of basement-cover sequences through recumbent folding and remobilization of uranium mineralization along reactivated strike-slip faults (Cosi et al., 1992; Loris et al., 1997; Kampunzu and Cailteux, 1999; John et al., 2004).

Tectonic uplift and rapid erosion followed final collision and resulted in the deposition of rippled siltstones of the Biano Group/Subgroup (Master et al., 2005) which is interpreted as a continental molasse (Kampunzu and Cailteux, 1999; Wendorff, 2003). Siltstones of the Biano Subgroup are not metamorphosed and represent the youngest unit of the Katanga Supergroup with a maximum age of 573 ± 5 Ma based on $^{40}Ar/^{39}Ar$ dating of detrital muscovite grains (Master et al., 2005). Cooling ages in the range 512–470 Ma determined by K–Ar and Rb–Sr dating of muscovite and biotite from the Domes region (Cosi et al., 1992; John et al., 2004), represent the final post-metamorphic ages in the Lufilian Arc. No precise dating of the third phase of the Lufilian Orogeny, the Palaeozoic Chilatembo phase of Kampunzu and Cailteux (1999) is available, but it may be bracketed between the ca. 530 Ma collision event and the 512 Ma cooling age of micas in the Domes Region. The Chilatembo phase is represented by open mesoscopic folds and structures transverse to the trends in the Lufilian Arc (Cosi et al., 1992; Kampunzu and Cailteux, 1999).

In a recent re-interpretation of the Katangan lithostratigraphy and Lufilian orogenic event Wendorff (2003) has proposed an additional younger lithotectonic unit, the Fungurume Group, which is a sedimentary synorogenic complex of continental red beds (Mutshi Formation), marginal marine carbonates (Dipeta Formation) and olistostromes (Kambove Formation) formed by mass gravity flows and erosion of the advancing thrust sheets during the Lufilian Orogeny, and deposited as olistostromes in the Katangan foreland basin (Wendorff, 2000a,b). According to Wendorff (2003), the Fungurume Group is partly coeval with the Biano Subgroup. Although the debate on the Katangan tectonic (mega)breccias is outside the scope of this paper, it is worth noting that both previous and recent data pertaining to structural, lithological, petrographic, geochemical, geochronological studies (e.g., Demesmaeker et al., 1963; Cailteux and Kampunzu, 1995; Kampunzu and Cailteux, 1999; Jackson et al., 2003; Cailteux et al., 2005a,b; Kampunzu et al., 2005; Batumike et al., 2007), and to unpublished C–O isotopic data (AMIRA, 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 contradict this interpretation.

Stratigraphic gaps between the Roan subgroups have been attributed to former evaporites (Cailteux, 1983, 1994; De Magnée and François, 1988; Cailteux and Kampunzu, 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, 1973b; Cailteux, 1983; De Magnée and François, 1988). Jackson et al. (2003) have gone further to propose that allochtonous salt tectonics may explain the occurrence of the enigmatic mega- and gigabreccias on the Copperbelt which underlie 25,000 km^2 and contain gigaclasts 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 overlying strata and later resulted in northward extrusion of evaporite and carbonate-dominated sediments and ores over autochtonous strata during Lufilian deformation, and eventually culminated into 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 Mindola/R.A.T., Kitwe/Mines and Kirilabombwe/Dipeta subgroups (Table 1) with the most important orebodies in carbonate dominated allochtonous units of the Mines Subgroup in Congo and within more siliciclastic units (sandstone, siltstone, marl and shale) of the laterally equivalent Kitwe Subgroup in Zambia (Mendelsohn, 1961c; Binda, 1994; François, 1974; Lefebvre, 1974; Fleischer et al., 1976; Cailteux 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 syngenetic to epigenetic (McGowan et al., 2003) still exist, a mineralized Palaeoproterozoic basement with copper-bearing gneisses (Voet and Freeman, 1972) and porphyry-type copper deposits (Wakefield, 1978) is the most plausible source of detrital material for the ore-bearing units. Ore formation involved multistage syngenetic and early to late diagenetic processes of metal concentration from basinal brines, with some remobilization during orogenic metamorphism (e.g., Garlick, 1961; Bartholome, 1974; Cailteux, 1986; Sweeney et al., 1986, 1991; Annels, 1989; Binda, 1994; Cailteux et al., 2005b; Selley et al., 2005). The syngenetic–diagenetic to remobilized origin of the mineralization is supported by microthermometric studies of pre-tectonic, syntectonic and post-tectonic fluid inclusions in gangue minerals which show that the ore fluids varied from low-temperature (70 to 150 °C) basinal brines to high-temperature metamorphic fluids (≥200 to 400 °C) with variable salinities (8 to >23 wt.% NaCl equivalent) (Pirmolin, 1970; Ngongo, 1975; Audeoud, 1982; Sweeney, 1987; Richards et al., 1988a; Annels, 1989; Greyling et al., 2005, El Desouky 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

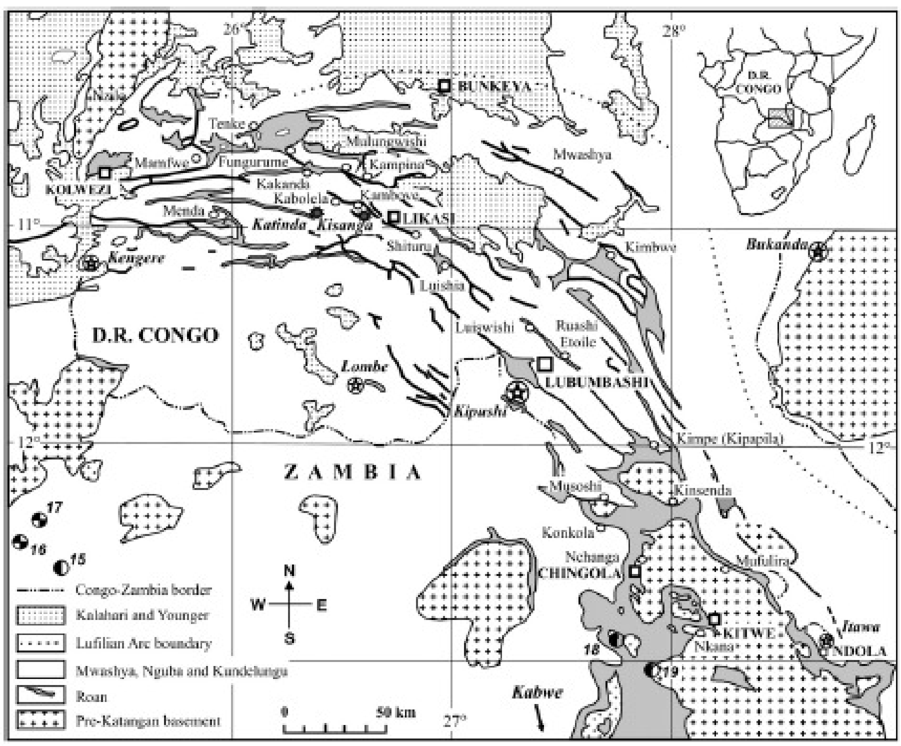

Fig. 3. Location of the main ore deposits and geological sites in the Central African Copperbelt (modified from the Geological Map of the Zambian Copperbelt, 1961; François, 1974; Cailteux et al., 1994). 15 to 19 are unnamed occurrences (see Fig. 2).

metres long) syndiagenetic in origin and containing little or no Zn and Pb. In contrast, carbonate-hosted Zn–Pb–(Cu)–(V) deposits and prospects occur mainly as irregular pipe- to vein-like bodies in various tectonic zones of the Lufilian Arc, the Zambezi and Mozambique Belts as well as the Kundelungu Aulacogen or palaeograben (Fig. 2). They include the major epigenetic Kipushi and Kabwe sulphide deposits which are hosted in carbonate units of the Nguba Group in Congo and the Kirilabombwe Subgroup in Zambia, respectively. Metal concentrations vary from dominantly Zn–Pb to either Pb- or Zn-rich occurrences, including the nonsulphide willemite Zn prospects in the Lusaka area (prospects 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 Kaponda, Kakontwe, Kipushi and Katete Formations of the Nguba Group (Table 1).

The Kaponda Formation, as defined informally by Intiomale (1982), corresponds broadly to the "Formation des Argillites Rubanées et du Faux Calcaire de Kakontwe" of Buffard (1978, 1988). It includes finely (mm-scale) bedded, greyish (fresh rocks) or yellow to reddish (altered rocks) dolomitic shales or shaly dolomicrites (e.g., in the Likasi area), evolving laterally into finely laminated and fine-grained dolomitic sandstones and sandy shales (e.g., in the Mwashya–Bunkeya areas; 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 lenticular beds. A marker horizon of stromatolitic dolostone, termed "Dolomie Tigrée" (Tiger Dolomite), occurs at the base of the Kaponda Formation (François, 1973a; Intiomale and Oosterbosch, 1974; Buffard, 1978, 1988; Intiomale, 1982; Batumike et al., 2007). The "Dolomie Tigrée" is a finely laminated blue-grey to dark grey, sometimes cherty and carbonaceous dolostone, calcareous in places. Dark, tortuous, lenticular cherty and dolomicritic layers alternating with lighter dolomicritic layers form the tiger texture and commonly highlight slumping structures in this dolostone.

The Kakontwe Formation, up to 340-m thick (e.g., at Kipushi), is a regional marker horizon representing an evaporite-rich dolomitic and shaly succession typical of an intertidal environment (Buffard, 1978, 1988), subdivided into three sub-units at Kipushi (Intiomale, 1980, 1983). The lower unit includes pyrite-rich, light grey massive dolostone with relics and pseudomorphs after gypsum, carbonaceous matter, and tortuous (enterolithic folds) dark layers referred to as "fluidal texture" by the mining geologists. The middle unit includes massive to finely bedded, light grey to purplish, pseudo-oolitic calcareous dolostones. Petrographically, these rocks include micritic mudstone, intra-sparite, pelsparite, oncosparite, and oncomicrite debris floating in dolomicrite desiccation breccias (Buffard, 1978, 1988). Well preserved oncolites provide a marker horizon at the top of the middle Kakontwe unit. Some organic relics related to "Tentaculite" (spicular) type species were noted (Hacquaert, 1933). Minor disseminated stratiform pyrite and chalcopyrite occur in this middle unit, which also contains anhydrite and gypsum relics. The upper Kakontwe unit is a dark grey, stratified, calcarous and carbonaceous dolostone with intercalations of fine carbonaceous layers and black cherts.

The Kakontwe Formation is overlain by the Kipushi Formation, a finely bedded black carbonaceous dolomite unit, up to 100-m thick (e.g., at Kipushi), characterized by black chert lenses and whitish oncolites, slump structures and lenticular grey-brown dolomitic shale (Buffard, 1978; Intiomale, 1982; Batumike et al., 2007).

The overlying Katete Formation in the southern areas (also named "Série Récurrente" by the mining geologists in Kipushi) contrasts with the Kipushi Formation by the occurrence of laminated, purple to whitish, albite-bearing calcarous and talcose dolostone 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 slaty or fracture cleavage is displayed by the trend of talc–albite–quartz lenses in this shaly unit, with the sulphide grains elongated parallel to the cleavage. The Kipushi and Série Récurrente

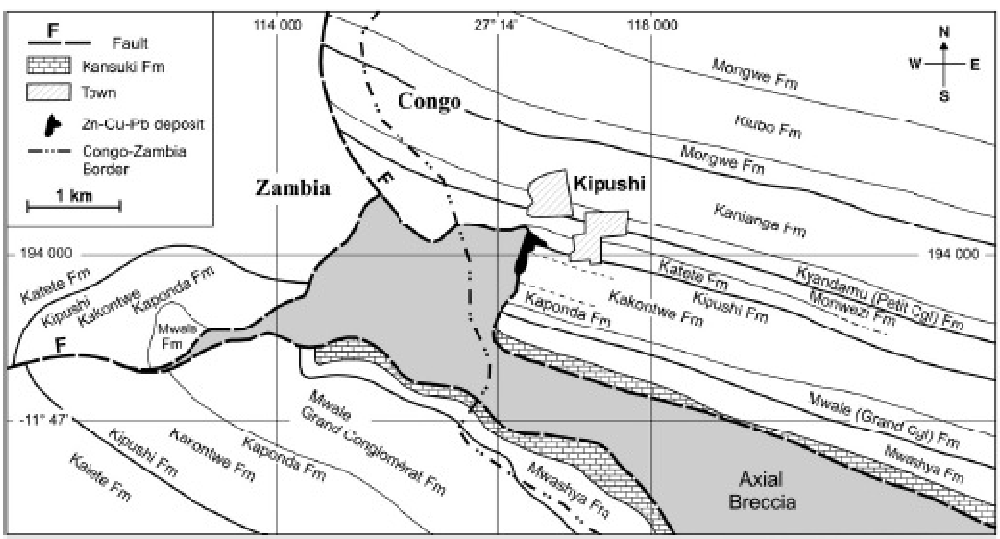

Fig. 4. Geological map in the Kipushi area (modified from Gécamines geological map, 1971).

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 towards the north (e.g., at Kakontwe).

3.1.1. *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 6,622,116 tons Zn and 4,082,275 tons Cu from 1922 to 1993 when operations were suspended. The in-situ ore grades averaged 11.03 wt.% Zn and 6.80 wt.% Cu. Ore has been proven to a depth ca. 1800 m, but mine development stopped at 1250 m depth. The remaining ore resources down to the 1500 m level are estimated at >5 Mt Zn, >500,000 tons Cu, and >100,000 tons Pb from ores averaging 21.4 wt.% Zn, 2.1 wt.% Cu and 0.88 wt.% Pb with additional trace metals of Cd (763 ppm), Co (100 ppm), Ge (68 ppm), Ag (28 ppm) and Re (3 ppm) (Cailteux, 1988, 1992). Other rare metals include As, Ga, Mo, Bi, Hg, Ni, Sb, Se, Sn, Te and V (De Vos et al., 1974; Intiomale and Oosterbosch, 1974).

The Kipushi deposit is hosted on the northern flank of a regional NW–SE trending anticline characterized by a faulted axial core filled with a megabreccia (the "Axial Breccia"; Fig. 4). The dip is 60–70° 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., arkosic sandstones, metabasic rocks associated with white talcose dolomite of the Dipeta Subgroup, and rocks of the Kakontwe Formation) (Briart, 1948; Intiomale, 1982). The dolomite of the Dipeta Subgroup and associated metabasic rocks are typical of the Zambian-type Kirilabombwe unit (Cailteux et al., 1994, 1995). The Axial Breccia is of the breccia type that generally underlies the Katangan thrusts and interpreted as a result of the Kolwezian (D_1) fold-and-thrust phase of the Lufilian orogeny (Demesmaeker et al., 1963; Intiomale and Oosterbosch, 1974; Cailteux and Kampunzu, 1995; Kampunzu and Cailteux, 1999).

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) (Intiomale and Oosterbosch, 1974; Intiomale, 1982). Geometrical relationships indicate that the "Cyclopean Breccia" cross-cuts the Axial Breccia and post-dates the Axial Fault (Intiomale and Oosterbosch, 1974; Intiomale, 1982). The Cyclopean Breccia is characterized by a branching pattern in plane view and mostly contains fragments of the enclosing dolomites of the Kaponda and Kakontwe Formations. Some breccias are similar to solution collapse breccias and contain fragments of reddish-brown ironstones, with a yellow indurated matrix made of mudstone in places. The pipe-like main orebody is irregular to elliptical in cross-section with an axial trend of 28° NE, 200 to 600-m long and 20 to 60-m thick with an average dip of 70° NW (Fig. 6). The orebody generally occurs along the Kipushi Fault and forms discordant offshoots within the cap carbonates of the Kakontwe and Kipushi Formations, whereas it is largely sub-concordant in the alternating dolomitic shales and dolomites of the Katete Formation

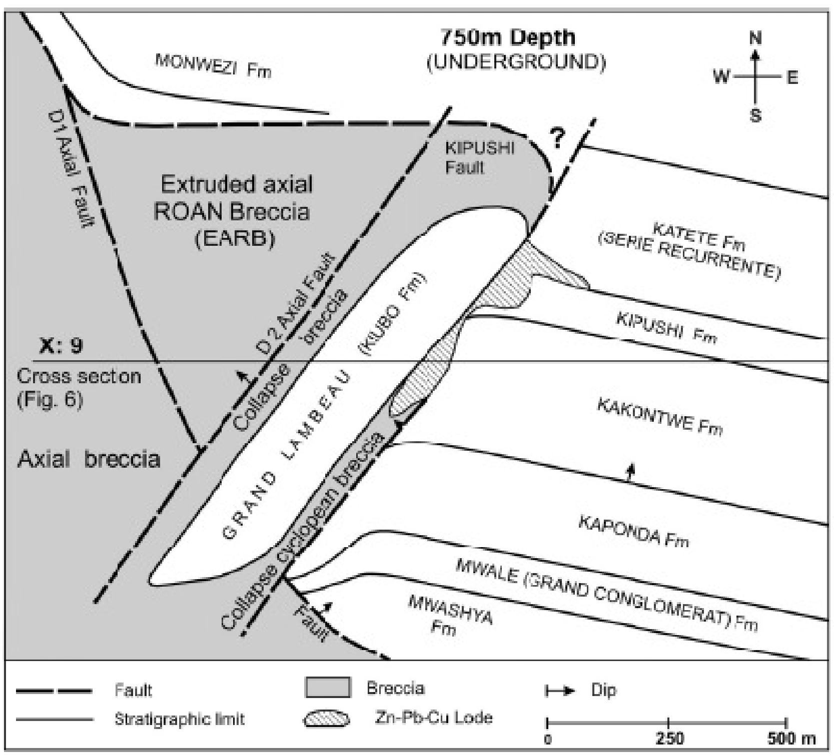

Fig. 5. Schematic map view of the Kipushi deposit underground structural features at 750 m depth (modified from Gécamines geological map). Localisation of cross-section X: 9 (Fig. 6).

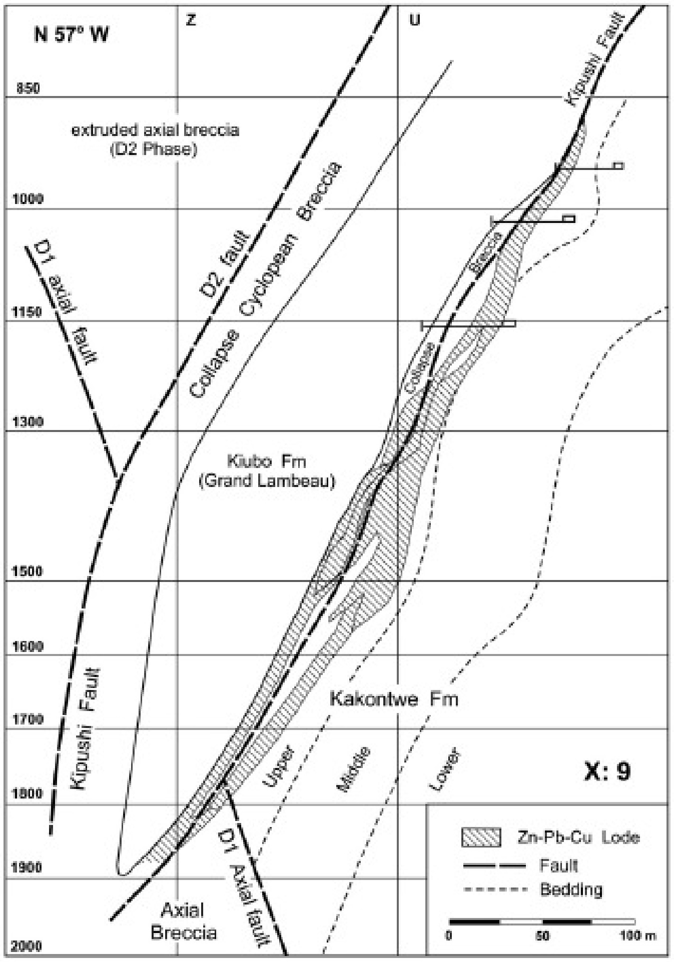

Fig. 6. Kipushi deposit: underground ore and structural features at cross-section X: 9 (modified from Intiomale, 1982).

(Figs. 5–9). 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 km-scale block of stratified carbonate-rich shales, siltstones and fine-grained sandstones of the Kiubo Formation (Kundelungu Group) enclosed in the "Cyclopean Breccia" (Intiomale, 1982).

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

Features indicating hydrothermal alteration in the Kipushi deposit include: (1) dolomitization of the Kakontwe limestone over a distance of 200 m from the pipe (Thoreau, 1928); (2) silicification of the wallrock dolomite; and (3) occurrence of black amorphous organic matter in the footwall dolomite up to ca. 40 m from the contact with the "Cyclopean Breccia"; (4) chloritization along ores contacts and fractures; (5) kaolinization of feldspars in sandstone of the "Grand Lambeau"; and recrystallization of carbonate and quartz in the orebodies (Intiomale, 1982).

The petrology of the ores in the Kipushi deposit has been documented for a period of more than 50 years (e.g., Thoreau, 1928; Masuy, 1938; Legraye, 1931; Viaene and Moreau, 1968; De Vos et al., 1974; Dimanche, 1974; Intiomale and Oosterbosch, 1974; Intiomale, 1982; Briart, 1948; Francotte, 1963). The primary ore sulphide minerals include, in order of decreasing abundance: sphalerite, chalcopyrite, bornite, chalcocite, pyrite, arsenopyrite, tennantite, and galena, with accessory, briartite, germanite, reniérite, betechtinite, carrollite, cobaltite, linnaeite, molybdenite, gallite, cosalite, bismuthinite, tungstenite, and stromeyerite (Intiomale and Oosterbosch, 1974). Secondary supergene minerals that occur in the superficial oxidized

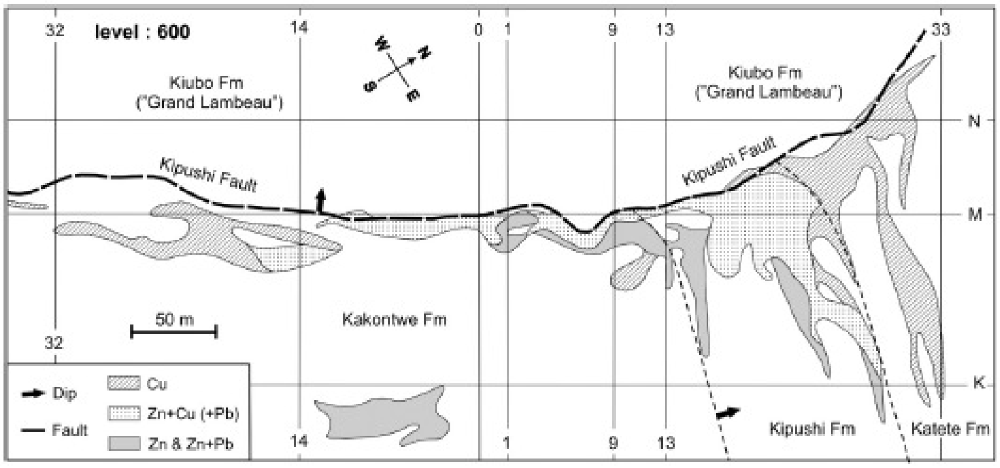

Fig. 7. Kipushi deposit: underground ore and structural features at level (Z) 600 (modified from Intiomale, 1982).

zone of the deposit and are not relevant for genetic interpretations, include cerussite, malachite, smithsonite, calamine, cuprite, chalcocite and, accessory, zincite–hydrozincite, aurichalcite, azurite, brochantite, chalcanthite, beaverite, anglesite, veszelyite, pseudomalachite, pyromorphite, vanadinite, cuprodescloizite, atacamite, dioptase, chrysocolla, willemite, native copper and silver (Intiomale and Oosterbosch, 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 Cd-rich sphalerite + pyrite + arsenopyrite + gallite + tennantite + chalcopyrite + galena. This ore type contains ≥ 7.0 wt.% Zn, <0.3 wt.% Pb and < 2.0 wt.% Cu;
(2) Zn–Pb ore with a simple mineralogy including brown to dark brown sphalerite (3.6–6.7 wt.% Fe) + pyrite + galena + gallite + tennantite + chalcopyrite. This ore type contains ≥7 wt.% Zn and ≥0.3 wt.% Pb, with Cu <2.0 wt.%. The highest Ag contents (up to 400 ppm) occur in the Zn–Pb veins and discordant chimney-type orebodies;
(3) Cu ore (≥1.0 wt.% Cu, <3.5 wt.% Zn) contains chalcopyrite, bornite, sphalerite, tennantite, reniérite, pyrite, ±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 3.5 wt.% ≤ Zn < 7.0 wt.% and ≥ 1.0 wt.% Cu, or ≥ 7.0 wt.% Zn and ≥ 2.0 wt.% Cu. The mineralogy is very complex and reflects the combination of Cu-rich and Zn–Pb-rich ores as described above;
(5) Massive pyrite.

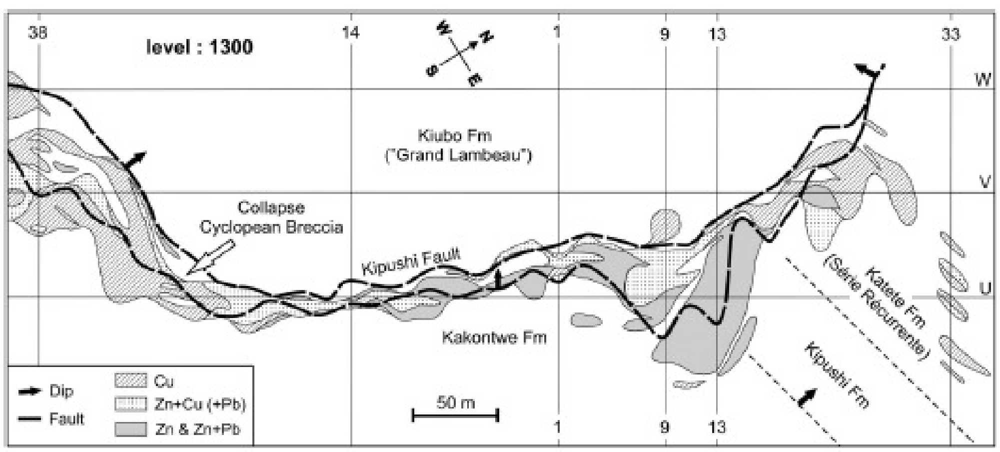

Fig. 8. Kipushi deposit: underground ore and structural features at level (Z) 1295, called 1300 (modified from Cailteux, 1988).

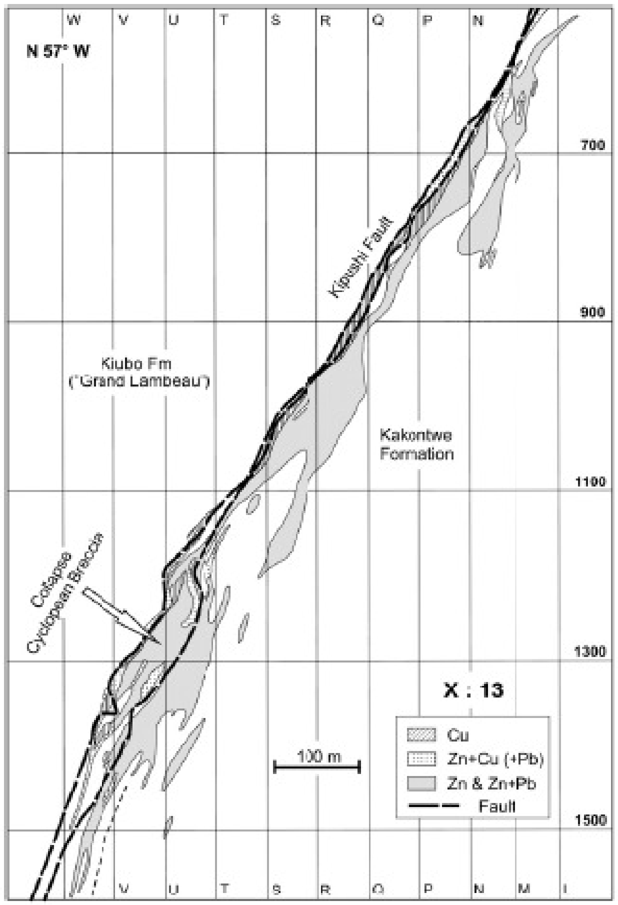

Fig. 9. Kipushi deposit: underground ore and structural features at cross-section X: 13 (modified from Cailteux, 1988, 1992).

The different ores types show a coherent zonal distribution with respect to host lithologies (Intiomale, 1982; Cailteux, 1988, 1992). From the surface down to the ca. 1500 m level (Figs. 7–9) the pipe-like orebody is characterized by: (1) predominantly Cu-rich ores in shales and carbonates of the Katete 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 Kakontwe Formation; (4) lenticular Zn–Cu or Cu ore masses parallel to the Kipushi Fault in the central to lower carbonates of the Kakontwe Formation and locally in the "Cyclopean breccia"; (5) Zn–Pb ores rimmed by massive pyrite and arsenopyrite (generally converted into ironstones with goethite and hematite in the superficial oxide zone). The latter ores occur as "chimneys" cross-cutting the Kakontwe Formation along north–south oriented fractures parallel to the northern part of the Kipushi Fault (Fig. 10). The Kaponda Formation contains massive pyrite, but also sub-economic disseminated sphalerite and chalcopyrite close to the Kipushi Fault. Locally, the "Grand Lambeau" contains Cu mineralization within sandy beds of the Kiubo Formation close to the "Cyclopean breccia." Below the 950 m level (Figs. 9 and 10), the main pipe-like orebody diverges into a central Zn or Zn–Cu–Pb-rich branch and an external Zn-rich branch. Below the 1350 m level, the concentration of Zn in the Zn–Cu ores decreases while the amount of Fe progressively increases. In general the distribution of the ores indicates that Zn and Pb are preferentially hosted in impure carbonate lithologies containing some SiO_2 (5 to 10 wt.%), while the Cu mostly occurs in fractured rocks. Ge- and Ga-rich ore masses occur in both the Cu-rich and Zn–Cu–(Pb) mixed ore types.

The distribution of cobalt amounts down to the 1000 m level is in the range of 200–300 ppm in ores from the northern part of the deposit (associated with the Katete and Kipushi formations), while ores from the southern part (associated with the Kakonwe Formation) average 50 ppm cobalt (Intiomale and Oosterbosch, 1974). Moreover, between 1150 and 1300 m levels (Cailteux, 1988) cobalt appears mostly associated with copper ores, with average amounts of 165, 178, and 115 ppm in the Cu, Zn–Cu, and Zn ores, respectively, in the northern part of the deposit (global average of 166 ppm), compared to values of 47, 83, and 54 ppm in the southern part (global average of 59 ppm).

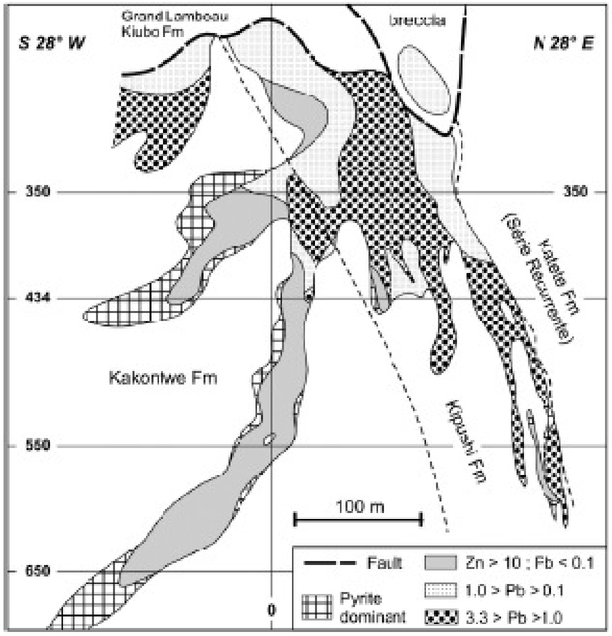

Fig. 10. Kipushi deposit: underground Zn–Pb–Fe ores distribution and structural features at cross-section subparallel to the northern part of the Kipushi Fault between level (Z): 200 and 700 (modified from Intiomale and Oosterbosch, 1974).

Paragenetic studies of the ores show the following general sequence of ore deposition, from the earliest to the latest sulphides (De Vos et al., 1974): (1) pyrite–arsenopyrite; (2) sphalerite; (3) chalcopyrite–tennantite–germanite–briartite; (4) bornite–chalcocite; (5) reniérite. Based on the chemical composition of the sulphides and their parageneses, Intiomale and Oosterbosch (1974) suggested the occurrence of two major successive primary mineralizing phases: (1) a Fe–As–Zn phase associated with minor Cu, Cd, Bi, Ge and Ga; and (2) a Cu phase characterized by an early Co-bearing chalcopyrite and a later Ag-bearing bornite paragenesis. 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 phase involved replacement of earlier sulphides and precipitation of tennantite, Bi-, Ga- and Ge-bearing chalcopyrite, (Cu-bearing) sphalerite, galena, briartite and reniérite. The interplay of these two mineralizing phases ultimately resulted in the formation of mixed Zn–Cu–(Pb) ores characteristic of the typically complex primary sulphide mineralogy at Kipushi.

3.1.2. Kengere

Kengere is located ~50 km south of Kolwezi and is the westernmost Zn–Pb deposit of the Copperbelt in Congo (Figs. 2 and 3). It has been previously mined at a small scale for Pb (10,000 tons Pb at 60 wt.% Pb) up to 1949, and unmined resources amount to ca. 63,200 tons Zn at 26.9 wt.% Zn and 7000 tons Pb at 5.6 wt.% Pb (Cailteux, 1989 and references therein).

The local lithostratigraphy of the mineralized zone includes the Kaponda, Kakontwe, and Kipushi Formations (Table 1, Fig. 11). Both Kaponda and Kakontwe rocks are characterized by the occurrence of black amorphous organic matter, and the barren Kipushi Formation is locally affected by fracturing and minor quartz–carbonate recrystallization. The deposit is associated with a north-trending fault (Fig. 11) cutting across Nguba Group rock units (Mwale, Kaponda, Kakontwe and Kipushi Formations) and is located a few hundred metres south of a major NE–SW trending fault zone with a (mega)breccia (Fig. 10). The major fault zone is subparallel to the axial planes of folds in the area.

The Kengere ore deposit is hosted in fractured carbonates and breccias developed in the contact zone between the Kaponda and Kakontwe Formations and it pinches out at ca. 110 m depth (Figs. 11 and 12). The 3 to 10-m thick Zn-rich orebody intersected in drillholes consists 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 ores show the following primary paragenetic sequence, from the earliest to the latest sulphides (Intiomale, 1982): pyrite, Fe–Cd-bearing sphalerite, and Ag-bearing galena. Based on the chemical composition of the sulphides and their parageneses, Intiomale (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 Cd and Ag during which sphalerite and galena were formed. The sulphides have been altered into secondary Zn–Pb–(Cu) oxide minerals (cerussite, smithsonite, calamine, and locally traces of chrysocolla) in the superficial oxide zone.

3.1.3. Lombe

This Zn–Pb deposit is located in the central-southern part of the Congo Copperbelt (Figs. 2 and 3) along a fault in the contact zone between the Katete and Kipushi Formations (Fig. 13). A major NE–SW trending fault zone associated with the Mwale Formation is located ca. 12 km south of the Lombe deposit (Fig. 13). This major fault zone contains metabasic rocks of the Dipeta Subgroup. Ore resources down to

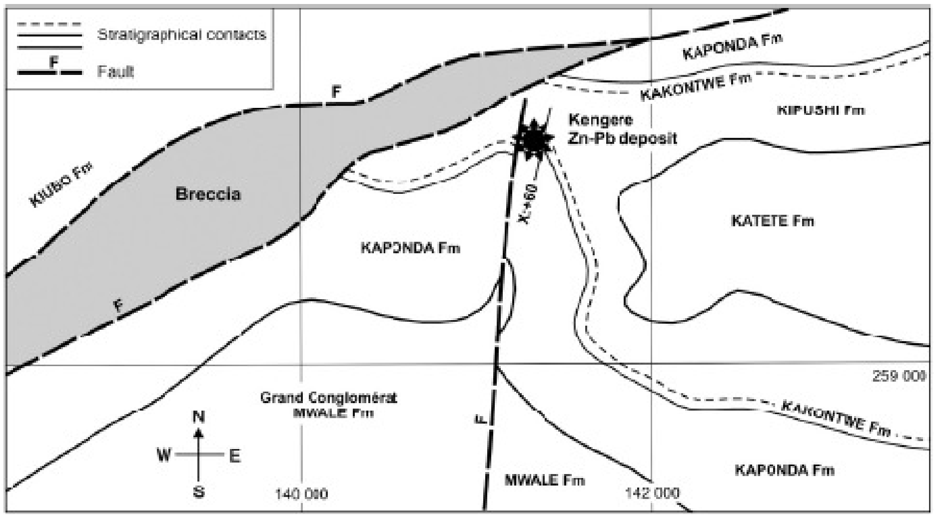

Fig. 11. Geological surface map of the Kengere area (modified from Intiomale, 1982; François, 1965; Cailteux, 1989).

a depth of 65 m below the surface amount to ca. 9300 tons at 31 wt.% Zn and 1600 tons at 5.4 wt.% Pb (Cailteux, 1989). Lenticular sub-economic (≤1 wt.% Cu) zones of syngenetic disseminated chalcopyrite and bornite occur in the upper beds of the Katete Formation (Intiomale, 1982).

The main orebody at Lombe 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 (Intiomale, 1982; Cailteux, 1989). A second orebody was intersected at ca. 85 m depth below a reverse fault (Fig. 14).

The ores show the following primary paragenesis, from the earliest to the latest sulphides (Intiomale, 1982): pyrite, sphalerite, tennantite,

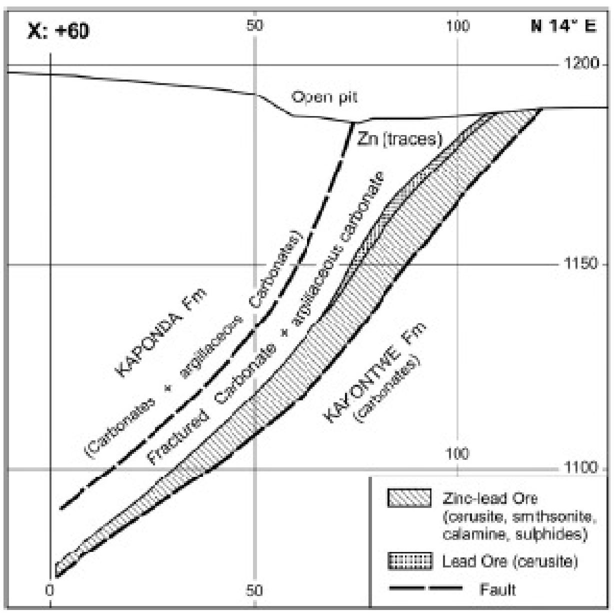

Fig. 12. Map view of the Kengere ore deposit stratigraphy and structural features at cross-section X: +60 (modified from Intiomale, 1982; François, 1965; Cailteux, 1989).

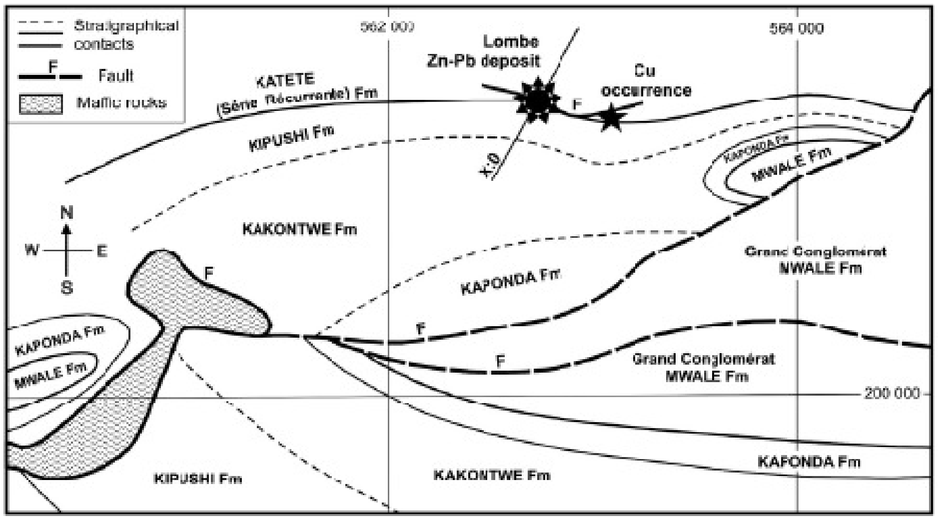

Fig. 11. Geological surface map of the Lombe area (modified from Intiomale, 1982; François, 1965; Cailteux, 1989).

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

At Lombe, syngenetic disseminated chalcopyrite and bornite occur as lenticular sub-economic (≤1 wt.% Cu) bodies hosted in the upper beds of the Katete (Série Récurrente) Formation (Intiomale, 1982).

3.1.4. Other similar occurrences in Congo

Dikulushi, located ~20 km to the west of the lake Mweru, in the northeastern part of the Lufilian foreland, is a low-temperature hydrothermal Cu, Zn, Pb, and Ag ore deposit with >165,000 tons Cu and 517 tons Ag (Lemmon et al., 2003). The ores deposited in a complex set of three groups of faults that created favourable conditions for mineralizing fluids circulation (Haest et al., 2007b). This intense fracturing is related to the D-1 and/or D-2 deformation events of the Lufilian orogeny (according to Kampunzu and Cailteux, 1999). Two generations of sulphides were identified (Dewaele et al., 2006; Haest et al., 2007a): (1) arsenopyrite, followed by pyrite + sphalerite, and chacopyrite, as well as paragenetically late minor tetrahedrite–tennantite, galena, bornite and chalcocite; (2) massive Ag-bearing chalcocite (digenite), associated with hematite and barite. The first generation sulphides are hosted in a breccia of tectonic origin and in brecciated Mongwe Formation rocks of the Kundelungu Group (Table 1) probably related to a D1-fold-and-thrust structure. The chalcocite-dominant and economically most important second generation of vein-type ore developped within a complex of faults in sandstones interbedded with argillites and intraformational breccias of the Mongwe and Kiubo Formations (Lemmon et al., 2003; Kanda Nkula et al., 2003; Dewaele et al., 2006; Haest et al., 2007b). In the superficial zone the sulphides are altered to secondary oxide minerals (malachite, chrysocolla, and azurite). This deposit is interpreted of similar origin as the Zn–Pb–Cu deposits in the copperbelt (Kanda Nkula et al., 2003; this paper).

Several authors (Van Aubel, 1928; Lefebvre, 1976; Intiomale, 1982; Cailteux, 1983) have reported Zn–Pb occurrences in the Roan Group at

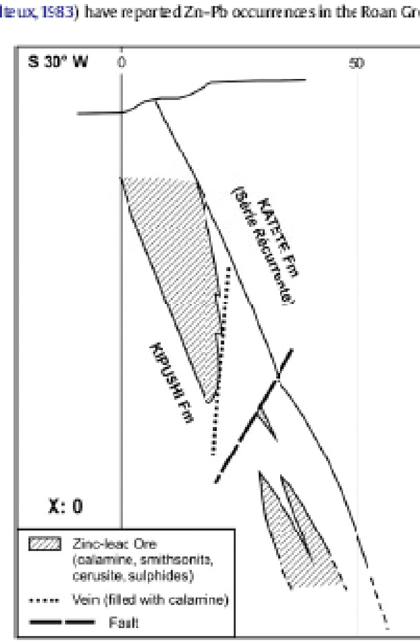

Fig. 14. Map view of the Lombe ore deposit, stratigraphy and structural features at cross-section X: 0 (modified from Intiomale, 1982; Autenne, 1936; François, 1965; Cailteux, 1989).

Mulungwishi, Kampina, Kabolela, and Ruashi (Fig. 3), generally hosted in quartz–dolomite veinlets composed of sphalerite–galena with associated pyrite and traces of chalcopyrite, or as pyrite-rich veinlets containing only a few percent of Zn and Cu. However, unlike the Zn–Pb mineralization in the Nguba and Kundelungu Groups, no economic or sub-economic deposit is known in the Roan Group in Congo.

Important masses of outcropping high grade iron oxide ores (mostly hematite) are hosted in carbonates of the Kakontwe Formation (e.g., Kisanga, Katinda, Lufunfu deposits; François, 1974). Kisanga, located close to Kambove, consists of two vein-type orebodies, 5 to 25-m thick and ~500-m long each at the base of the Kakontwe Formation, and separated by a 300-m wide barren zone. The ore includes trace amounts of Cu, Co, Zn, and Au, with relics of pyrite in depth. These iron oxide deposits probably represent gossans formed by the alteration of massive primary pyrite during recent superficial 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. Deposits 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 Fe, Mn, Au and Pb–Zn–Cu–(V) occurrences (Fig. 15). According to the local geologists (Taylor, 1954; Whyte, 1966; Kortman, 1972; Kamona, 1993) and to a recent review (Kamona and Friedrich, 2007), the Neoproterozoic lithostratigraphy of the Katangan in the Kabwe area includes, from the base to the top:

(1) a basal conglomerate resting unconformably on a Palaeo- to Mezoproterozoic basement complex largely made up of older granite–gneiss and younger Muva schist and quartzite as well as mafic lavas of uncertain age (Fig. 15);
(2) a mixed unit known as the Kangomba Formation (Moore, 1964; Cairney and Kerr, 1998) consisting of arkose, quartzite, and conglomerate at the base with overlying metasiltstone, schist, phyllite and dolomite at the top;
(3) a predominantly phyllite–dolomite unit with associated calcite–marble named the Nyama Formation.

As discussed by Kamona and Friedrich (2007) the lower units of the Kangombe Formation have previously been correlated to the Lower Roan of the Copperbelt and the upper units to the Upper Roan. The Kangomba Formation is part of the Kirilabombwe Subgroup and is equivalent to the Kibalongo and Bancroft Formations in Table 1. At Kabwe the upper part (Bancroft Formation) of the Kangomba Formation has been subdivided into the following units (Kortman, 1972): (1) a grey arenaceous dolomite; (2) a light grey massive dolomite hosting the main orebodies; (3) a grey slightly carbonaceous dolomite; (4) a dark carbonaceous dolomite; and (5) a grey to pink argillaceous dolomite with talcose partings. The Nyama Formation has been correlated to the Nguba Group (Moore, 1964; Intiomale, 1982), but it is also possible that it is equivalent to the Upper Roan, as indicated by the structural and geochronological data of Barr et al. (1978) for the Lusaka Dolomite, which is presumably equivalent to the Nyama Formation.

Nguba equivalent lithostratigraphic units at Kabwe have been observed by Taylor (1954), Kortman (1972), and Intiomale (1982). Intiomale (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 Conglomérat" (Mwale Formation) (Table 1); (b) a finely bedded dolostone alternating with carbonate-rich and carbonaceous shales, the "Schistose Dolomite," showing typical features similar to the "Dolomie Tigrée" marker horizon in Congo; (c) a grey to dark grey bedded dolomite including lenticular carbonaceous shales ("Carbonaceous Dolomite"); (d) light grey massive dolomite with frequent zones of recrystallized dolomite and locally fractured at the base. In this succession, the "schistose" and "carbonaceous" dolomites are interpreted as part of the Kaponda Formation. The massive Kabwe dolomite may thus correspond to dolostones of the Kakontwe

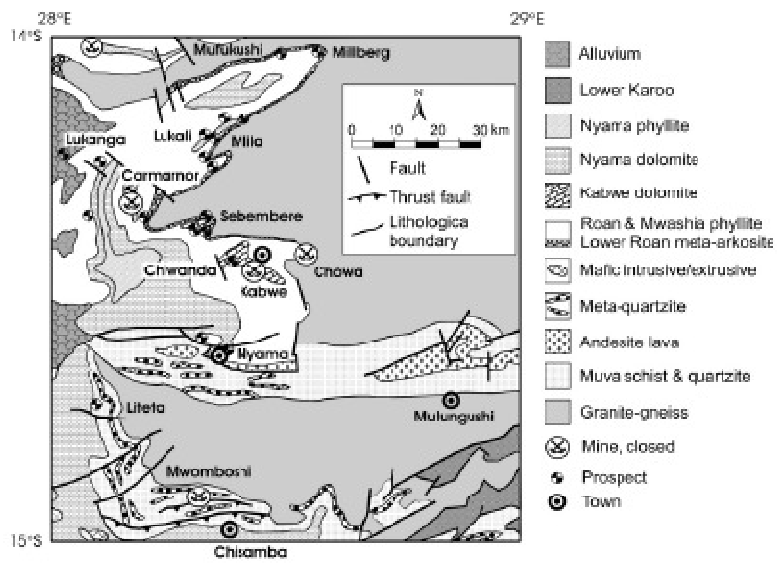

Fig. 15. Geology and distribution of Zn–Pb–(Cu)–(V) deposits, prospects and occurrences in the Kabwe region (modified from Kamona, 1993).

Formation. However, the Nguba units intersected by drilling occur along the Mine Club fault zone (Taylor, 1954) and have been interpreted as in-faulted Nguba units (Kortman, 1972).

The Kabwe mine produced Zn, Pb, V_2O_5, Ag, Cd and Cu over a period of 88 years (from 1906 to 1994) from a pre-production ore tonnage of 12.28 Mt averaging 25 wt.% Zn and 10.7 wt.% Pb (Kamona, 1993; Kamona and Friedrich, 2007). At mine closure in 1994, the remaining resources, largely in the No. 2 Zn–silicate orebody, were assessed as ~1.9 Mt at ca.13.4 wt.% Zn and 1.5 wt.% Pb. The relatively rare trace elements of Ge, Ga and In have never been produced from the ore since the Ge-bearing sulphides of reniérite and briartite were only discovered in 1991 (Kamona et al., 1991a,b; Kamona, 1993), by which time most of the Ge-bearing massive Zn–Pb ores had been almost mined out. Further investigations are required to establish the possibility of recovering trace metals such as Ge, Ga and In from the slag heaps.

Zn–Pb mineralization in the Kabwe area includes massive, disseminated and lateritic types (Kamona, 1993). The main massive Zn–Pb orebodies occur mostly in the massive dolomite of the Bancroft Formation, but disseminated mineralization also occurs in the overlying carbonaceous dolomite at Airfield (Kamona and Friedrich, 2007). Prospects with disseminated type of mineralization in dolomite include Carmanor, Lukali-Zn, Millberg and Chiwanda (Fig. 15). The disseminated mineralization is usually associated with an overlying lateritic horizon enriched in Zn, Pb and V as found at Airfield, Carmanor and Chiwanda.

The Kabwe deposit consists of massive Zn–Pb orebodies (Fig. 16) containing sphalerite, galena, pyrite, minor chalcopyrite, accessory briartite and reniérite that collectively constitute the primary ore mineral assemblage (Kamona, 1993; Kamona and Friedrich, 2007). Cores of massive sulphide orebodies are surrounded by oxide zones of silicate ore (willemite) and mineralized jasperoid that consists largely of quartz, willemite, cerussite, smithsonite, goethite and hematite, as well as numerous other secondary minerals, including vanadates, phosphates and carbonates of Zn, Pb, V and Cu. The ores are mainly hosted in the massive dolomite close to the faulted contact with a schistose talc-bearing dolomite (Fig. 16). Detailed decriptions of the individual orebodies at Kabwe, 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 Kamona and Friedrich (2007).

The pipe-like orebodies mainly occur along NE–SW trending faults as shown by the strike of the No. 5/6 orebody (067°) which is subparallel to that of the No. 3/4 (Fig. 16). The orebodies are clearly discordant to the host dolomite which has a local strike and dip of 290/65°NE. The ores are associated with a cemented breccia and are truncated by the Mine Club fault zone to the east (Fig. 17). The No. 5/6 orebody (Figs. 16 and 18) was the largest single orebody of massive Pb–Zn ore at Kabwe with a total pre-production tonnage of 6.1 million tons (Mt) and average grades of 28.8 wt.% Zn and 16.1 wt.% Pb (Kamona and Friedrich, 2007). The pipe-like orebody is typical of other major orebodies at Kabwe, but it becomes chimney-like (subvertical) below 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 a few metres from the orebodies but it may contain very finely disseminated diagenetic sulphides of sphalerite, galena and pyrite.

The Kabwe deposit is also associated with breccia bodies as documented by Whyte (1966), Kortman (1972) and Samama et al. (1991). According to Samama et al. (1991), the main features of these breccias are characteristic of a karstic origin. The collapse breccias are marked by a lithified brown yellow to reddish-brown mud matrix and can be seen to pass through crackle breccias and fissures cutting the host rocks. The banded structures in the internal sediments of the collapse breccias consist of solutional residues and sulphide precipitates filling interfragmental voids of the breccia. The rock fragments are lined with carbonates and ore minerals. The orebodies show a cross-cutting relationship to the surrounding rocks and stratification planes. However, the stratified indurated matrix of the breccia is broadly parallel to the NW–SE bedding in the host rocks. These features were considered to indicate a pre-kinematic emplacement of the deposit (Samama et al., 1991) but, as at Kipushi, they can also be interpreted to mark a syn-kinematic deposition.

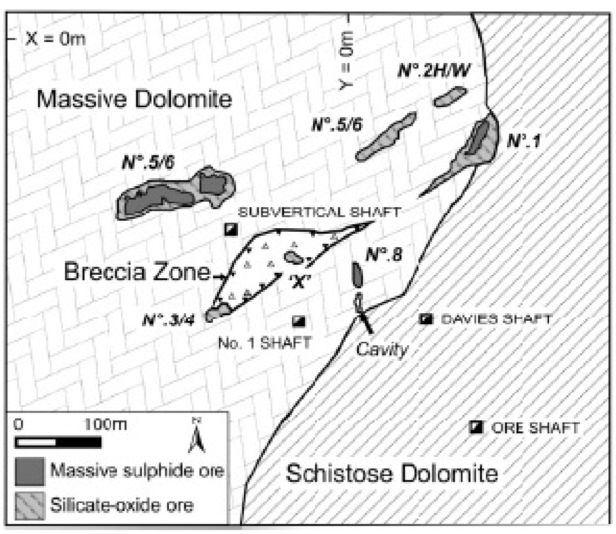

Fig. 16. Morphology and relative positions of orebodies on the 850 ft level at Kabwe mine area (based on mine data).

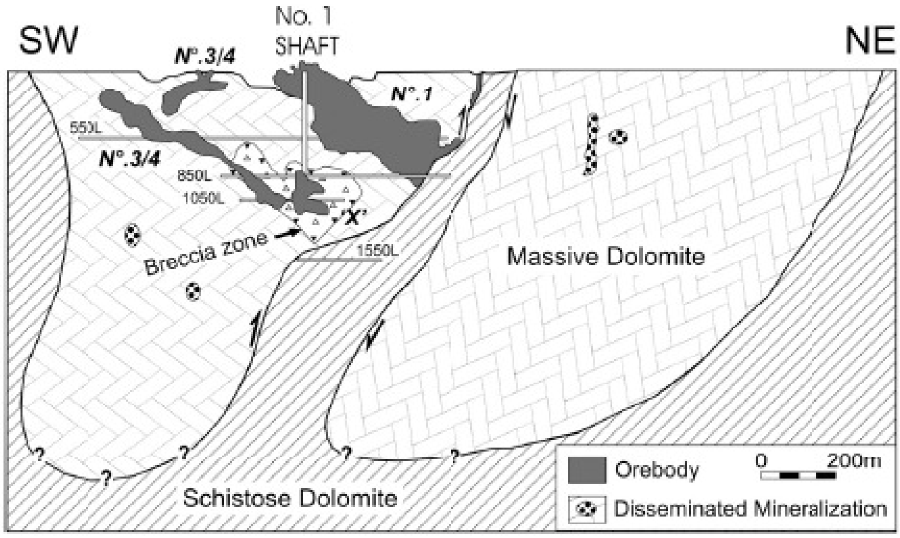

Fig. 17. Structural section through the N° 1, N° 3/4 and "X" orebodies at Kabwe mine (modified from Kamona et al., 1990).

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 (pseudomorphosed after pyrite) and deposition of the Zn–Pb massive sulphides;
(iii) emplacement of a very coarse to giant-grained (crystals up to 1 m), white pink dolomite around the No. 8 orebody (Fig. 16) believed to be of hydrothermal origin (Kamona, 1993, Kamona et al., 1999; Freeman, 1988b);
(iv) deposition of black organic matter in the mineralized breccia.

Pods of massive sphalerite up to 0.5 m wide occur within the major orebodies, and the No. 8 orebody is composed entirely of sphalerite (Kamona and Friedrich, 2007). Sphalerite generally contains low amounts of Fe (0.3–1.9 wt.%), Mn (0.01 to 0.11 wt.%), and some Cd (0.08 to 0.41 wt.%). Galena is subordinate to sphalerite in the massive Zn–Pb ores (No. 1, No. 3/4, No. 5/6, and 'X' orebodies) which have a Zn/(Zn + Pb) metal ratio of 0.63. The amount of galena is even less in the oxidized silicate ores (No. 2, SOB, "E," 2H/W' and Foundry) which have an average Zn/(Zn + Pb) ratio of 0.88. Galena contains Bi (~0.06 wt.%) and Ag (~0.03 wt.%), whereas trace amounts of Co (0.04–0.11 wt.%) and Ni (~0.02 wt.%) occur in pyrite. Chalcopyrite is characterized by significant Ge (0.19–0.63 wt.%) and very low concentrations of Zn (~0.05 wt.%). The Ge in chalcopyrite is due to the presence of exsolution intergowths of reniérite and briartite which also occur as inclusions in pyrite, galena and sphalerite (Kamona and Friedrich, 2007).

Mineral banding occurs locally in the sulphide ores and is typically caused by mm-wide interbands of galena–sphalerite or pyrite–sphalerite. Massive pyrite mineralization occurs marginal to some orebodies (e.g., 2 and 5/6 orebodies; Intiomale, 1982; Kamona, 1993) but also as oxidized fragments of ironstone (pseudomorphosed after pyrite) in all the orebodies. It seems that massive pyrite was deposited at an earlier stage of sulphide emplacement (Taylor, 1954; Kamona, 1993).

Deformation of the primary sulphides (pyrite, sphalerite, galena, chalcopyrite) is indicated by cataclastic textures, grain fracturing, lamellar twinning, bent cleavage planes, and recrystallization (Kamona, 1993; Kamona and Friedrich, 2007). The deformation indicates that the ores experienced a phase of low grade metamorphism (Kamona and Friedrich, 2007), possibly during the waning stages of the Lufilian orogeny at ca. 550 Ma (Porada and Berhorst, 2000).

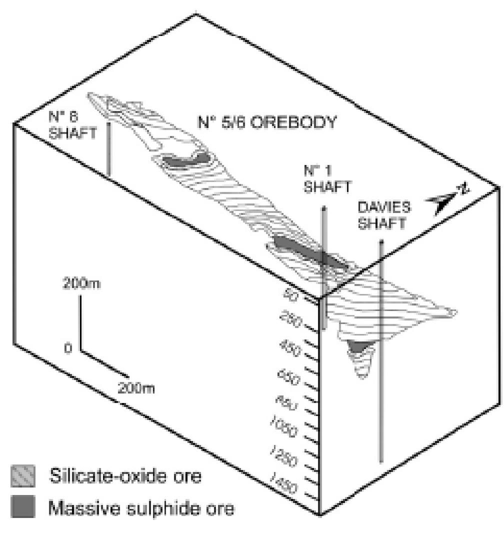

Fig. 18. Three dimensional view of the N° 5/6 orebody at Kabwe mine (based on mine data).

Numerous secondary and rare supergene minerals (Kamona et al., 1991a; Kamona, 1993 and references therein), that made Kabwe mineralogically famous include rare phosphates (tarbuttite, parahopeite, pyromorphite, hopeite, spencerite, scholzite, and zincian libethenite), vanadates (vanadinite, descloizite, mottramite), carbonates (smithsonite, cerussite, azurite, hydrozincite, aurichalcite, rosasite, and plumbian and zincian malachite), silicates (hemimorphite, chrysocolla and willemite), oxides (magnetite, hematite, goethite, zincite, psilomelane, wulfenite and cuprite), sulphates (anglesite, gypsum, linarite, and goslarite), sulphides (covellite, chalcocite, and galena), arsenates (beudantite, mimetite), and native copper.

3.2.2. Similar occurrences in Zambia

A number of smaller Zn–Pb–(Cu) prospects or deposits are known to occur in metacarbonates of the Katanga Supergroup. They include Millberg (315,000 tons at 3.7 wt.% Zn and 1.70 wt.% Pb), Mufukushi (6000 tons at 1.23 wt.% Cu and 1400 tons at 0.70 wt.% Zn), Carmanor (37,000 tons at 11.7 wt.% Zn, 1.40 wt.% Pb), Chiwanda (87,000 tons at 1.87 wt.% Zn) and Lukali (28,000 tons at 4.84 wt.% Zn) in the Kabwe region, as well as Lukusashi (32,000 tons Zn–Cu), and Kaungashi on the Copperbelt, Star Zinc (>42,000 tons Zn), Bob Zinc (32,000 tons Zn) and Excelsior in central Zambia and Semahwa Zinc in southern Zambia (Fig. 15; Sweeney et al., 1991; Kamona, 1993; Freeman, 1988a).

The lithostratigraphic position of the host rocks for most of these deposits is generally poorly constrained due to poor exposure and lack of fossil or geochronological data. The occurrence of massive dolomite, bedded dolomite ± chert, shale and, locally conglomeratic dolomitic sandstone at some localities (e.g., at Kaungashi and Lukali) may indicate the presence of lithological units comparable to the Kakontwe and Grand Conglomérat.

The Carmarnor, Lukali-Zn, Millberg and Chiwanda prospects (Fig. 15) are hosted in massive dolomite containing disseminated mineralization, pods and veins of sphalerite and galena (Kamona, 1993). The disseminated Zn–Pb mineralization is usually associated with an overlying lateritic horizon enriched in Zn, Pb and V (e.g., at Airfield, Carmarnor and Chiwanda). About 2000 tons of V-ore grading 18–19% V_2O_5 have been mined at Carmarnor from such residual lateritic soils containing descloizite above patchy to disseminated galena and sphalerite in dolomite (Cairney and Kerr, 1998).

At Mufukushi Cu–Zn mineralization occurs in a tremolite–dolomite schist overlying footwall quartzite (Cairney and Kerr, 1998) possibly equivalent to basal units of the Lower Roan. A Zn-rich zone typically overlies a Cu-rich zone with or without barren schist between the two zones. The mineralogy consists of cuprite, chalcocite, tenorite, sphalerite, chalcopyrite, bornite, malachite and chrysocolla. A similar metal zoning is also observed at Lukusashi, where Zn-rich ore (158,000 tons containing 6.4 wt.% Zn, 0.98 wt.% Pb, 0.15 wt.% Cu and 19.4 g/ton Ag) is associated with a Zn–Cu-rich ore (730,000 tons grading 1.55 wt.% Zn, 1.47 wt.% Cu, 0.62 wt.% Pb and 33.4 g/ton Ag (Freeman, 1988a).

The Semahwa Zinc prospect is located in the southern province of Zambia, 20 km north–northwest of Choma (Freeman, 1988a). The prospect is underlain by metapsammitic rocks containing sericite, biotite, garnet and kyanite with talc and tremolite layers in places. A mineralized drillhole intersection of 2.2 m contained disseminated pyrite, pyrrhotite, chalcopyrite and galena in a kyanite–garnet bearing biotite quartzite with grades of 0.18 wt.% Cu, 0.36 wt.% Pb and 0.64 wt.% Zn (Freeman, 1988a). Zinc in this unusual prospect is accommodated in gahnite, a zincian-spinel. The coexistence of kyanite and talc is diagnostic of whiteschists (Schreyer, 1973), indicating a high pressure type of metamorphism. In such rocks, garnet is common and results from the breakdown of chlorites whereas white mica is phengite. Biotite is generally non-existent or scarce in rocks equilibrated in high pressure type orogenic metamorphism (Chopin and Schreyer, 1983; Koons and Thompson, 1985), except in extremely Mg-rich rocks where it occurs as phlogopite (Bucher and Frey, 1994). This probably applies at Semahwa since the biotites analysed by microprobe in the Zn–Pb deposits in the Copperbelt are phlogopites (Kampunzu, unpublished data).

Kansanshi is a low-temperature Cu–Au deposit (~3.6 Mt Cu; Freeman, 1988a; Mining Magazine, 2005) located in the Domes area, and hosted in metamorphosed (greenschist grade) and hydrothermally altered carbonates of the Kakontwe Formation. The Grand Conglomérat, Kaponda (Dolomie Tigrée), and Kakontwe rock units form part of the succession in the area (Barron, 1999; Comet/ZCCM and Cyprus Amax documentation; observations of Binda, Cailteux and Kampunzu on representative drill cores during the IGCP 302 and 418/419 field trips in 1993 and 1999, respectively). Sulphide mineralization consists of both vein-hosted and finely disseminated stratiform sulphides that include pyrite, pyrrhotite, chalcopyrite, bornite (supergene digenite, chalcocite) with trace amounts of brannerite, molybdenite, silver, and gold.

4. Ore geochemistry

4.1. Mineral chemistry

Detailed accounts of the mineralogy of the Zn–Pb deposits in the Central African Copperbelt can be found in previous publications (e.g., Hubbard, 1913; Mennell, 1920; Thoreau, 1928; Legraye, 1931; Masuy, 1938; Guillemin, 1956; Francotte et al., 1965; Whyte, 1966; Viaene and Moreau, 1968; Intiomale and Oosterbosch, 1974; De Vos et al., 1974; Dimanche, 1974; Notebaart and Korowski, 1980; Intiomale, 1982; Braithwaite, 1988; Kamona and Friedrich, 1989, 1994, 2007; Kamona et al., 1991a,b; Kamona, 1993; Francotte, 1962). The most relevant data from these papers are discussed here and complemented by results of a recent study on drill core material from Kipushi (BGR, unpublished data).

Although minor local variations may exist, the following set of minerals is typical of massive Zn–Pb sulphide ores in the low grade metamorphic zone of the Copperbelt of Central Africa: sphalerite + pyrite + galena + chalcopyrite, with subsidiary ± arsenopyrite, ± gallite, ± tennantite, ± briartite, ± reniérite. Variations in the relative proportions of the three important sulphides (pyrite, galena and sphalerite) result in the identification of massive pyrite ore, galena-rich and sphalerite-rich ores, respectively.

The Zn-rich and Zn–Pb rich ores at Kipushi, which is the most complex deposit in the Copperbelt, also have a relatively simple mineralogical composition. The massive pyrite ores at Kipushi and Kabwe, which mark the earliest stage of sulphide precipitation, contain the same ore minerals as the Zn–Pb ores, but are characterized by high Fe (ca. 40 wt.%) and low Pb + Zn (<3 wt.%) concentrations. Pyrite is locally converted into iron oxides resulting in the ironstones which are common as fragments and also form the matrix in collapse breccias of the Kipushi deposit. The oxidation of massive pyrite to form goethite and hematite in the ironstones was accompanied by the precipitation of pyromorphite, vanadinite and descloizite as well as Mo enrichment in ferric oxides at Kabwe (Kamona, 1993).

Minor and trace element contents of various ore types are presented in Table 2. The polymetallic composition of the Kipushi ores is most notable, and is comparable only to deposits in the Otavi Montain Land of Namibia, such as Tsumeb, Kombat and Khusib Springs (Table 2; Lombaard et al., 1986; Melcher, 2003; Melcher et al., 2006). Besides highly variable concentrations of Cu, Zn, Pb and Fe, these deposits may carry anomalous Ag, As, Cd, Co, Ga, Ge, Mo, Re, Sb, Sn and W, but are usually low in Ni, Bi, and In. Whereas Kipushi, Kombat and Tsumeb also carry appreciable Cu, the Kabwe, Kengere and Lombe deposits are essentially Zn–Pb-rich with minor Cd, Cu, As, and low Ag, Ga, Ge.

The colour of the sphalerite is variable, generally from brown to dark brown at Kipushi, up to honey yellow at Kabwe. The darker sphalerite is Fe-rich (>3 wt.% up to ca. 7 wt.%) and contains gallite + tennantite + chalcopyrite exsolutions whereas the light variety has

Table 2
Elemental composition of Zn–Pb–(Cu) deposits in the Central African Copperbelt and Namibia: Kipushi (Intiomale and Oosterbosch, 1974; Cailteux, 1988; BGR, unpublished data), Lombe and Kengere (Intiomale, 1982; Cailteux, 1989), Kabwe (Intiomale, 1982; Kamona, 1993; Kamona and Friedrich, 2007), Khusib Springs (drill core KH26; Melcher et al., 2006), and Tsumeb (BGR, unpublished data; run of mill ore from Lombaard et al., 1986).

Deposit	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Lombe	Kengere	Kabwe	Khusib Springs	Tsumeb	Tsumeb
Orebody	Cu, Zn–Cu	Zn, Zn–Pb	(SR)	Cu	Zn–Cu	Zn, Zn–Pb	Cu (SR)	Cu–Ge	Cu–Zn	Zn–(Cu)	Zn–Pb	Zn–Pb	Zn–Pb	Cu–Pb–Zn	Pb–Zn–Cu	Run of mill ore
Position	> 1000 L	>1000 L	> 1000 L	1145–1300 L	1145–1300 L	1145–1300 L	1145–1300 L	787 L	1150 L	1270 L	DH-3 and 10	DH-10 and 11	UG 3/4 OB	KH-026	28–37 L	
Major and minor elements (wt.%)																
Cu	–	–	–	1.08–6.25	2.44–11.42	0.12–0.80	–	2.09–37.45	7.65–42.44	0.053–18.55	< 0.10–0.52	< 0.10	<0.10–0.13	0.05–41.63	0.39–36.16	4
Fe	–	–	–	–	–	–	–	1.17–26.40	5.72–11.20	6.94–32.3	6.20–11.10	4.40–6.90	1.20–3.55	0.05–13.00	0.07–13.00	1.5
Pb	–	–	–	0.01–0.27	0.14–1.21	0.02–2.96	0.01–0.05	0.0004–7.09	0.003–5.88	0.004–0.05	0.02–14.30	< 0.01–1.34	9.70–19.00	0.01–51.08	1.58–51.77	12
Zn	–	–	–	0.24–5.87	3.53–22.05	7.25–44.63	0.19–1.38	0.063–3.46	0.41–36.40	0.03–51.90	3.10–50.00	1.25–49.80	30.20–50.6	0.02–27.10	0.09–36.00	3
S	–	–	–	–	–	–	–	3.89–30.83	14.79–24.31	21.72–30.87	–	–	–	0.87–22.23	4.7–25.8	4
Trace elements (ppm)																
Ag	–	–	–	1–25	14–156	0–32	1–14	<5–398	15–6150	< 5–2830	16–188	3–5	28–95	121–3350	<5–679	100
As	1000–> 10,000	–	< 1000	–	–	–	–	405–23,180	479–9870	696–3480	190–6000	14–100	50–1450	177–47,000	53–52,400	10000
Bi	20–100	100	–	–	–	–	–	<0.02–1.18	0.11–1.42	0.28–25.39	–	–	–	< 1–6	<0.1–2.6	1
Cd	–	–	–	18–457	163–1514	196–2464	18–161	11–8940	99–2710	2.6–2850	1000–1800	1900–2000	65–800	5.2–780	34–8520	400
Co	200–> 10000	50	200–300	9–411	48–263	7–373	13–411	2–36	15–1018	0.8–1220	24–70	16–30	12–16	< 1–118	<1–350	5
Ga	15	15–2500	15	–	–	–	–	169–24,180	2.6–13.2	14.4–516	< 5–23	18–50	15–20	< 1–49	19–1130	<1
Ge	30–7000	40–50	30–80	1–130	3–206	2–275	1–151	51–15,408	11–17	32–90	< 4–38	< 4–16	6	< 1–230	0.6–1230	50
Hg	–	–	–	–	–	–	–	<1–64	3–27	< 1–84	–	–	–	< 1–51	<4–350	100
In	–	–	–	–	–	–	–	0.7–52	<0.1–0.9	< 0.1–12	–	–	–	< 0.4	0.17–34	<1
Mo	150	<10–33	–	–	–	–	–	<1–54	< 1–46	1.6–65	–	–	–	< 1–180	<2–6479	500
Ni	< 50–330	–	–	–	–	–	–	1–27	2–66	0.7–32	–	–	–	< 1–48	<1–267	20
Re	–	–	–	0–8	0–31	0–11	0–8	0.013–2.4	< 0.001–0.03	< 0.001–0.08	< 5	< 5	<5–24	< 0.01	0.02–271	<1
Sb	–	–	–	–	–	–	–	3–657	11–340	0.3–806	–	–	–	18–54,604	15–1080	150
Se	4	15	–	–	–	–	–	<5–69	< 3–24	< 3–71	–	–	–	8–237	6–1300	50
Sn	–	–	–	–	–	–	–	<1–180	< 1	< 1–44	–	–	–	< 1–133	<1–17	10
W	–	–	–	–	–	–	–	<1–5980	< 1	< 1–7	–	–	–	< 1–159	<1–178	

SR = Shale Récurrente; UG = underground; OB = orebody. BGR data for Kipushi are from drill cores on 787 (n = 19), 1150 (n = 7) and 1270 (n = 10) levels (L); for Tsumeb: 49 chips from four drill cores on 28, 30 and 37 levels.

<2 wt.% Fe (range 0.3–1.9 wt.%) and, apart from rare inclusions of briartite and reniérite (e.g., at Kipushi and Kabwe), is usually devoid of exsolutions (Intiomale and Oosterbosch, 1974; Kamona, 1993). At Kipushi, the Cd content in some sphalerite varies from 0.02 to 2.2 wt.% (Melcher, unpublished data); sphalerite may also contain significant amounts of Cu (up to 0.69 wt.%) and/or Co (from 20 to 820 ppm) (Intiomale and Oosterbosch, 1974). A light green variety of sphalerite containing 0.58 wt.% Cu, 0.18 wt.% Fe, and 0.018 wt.% Ni has been observed only in association with Ge (in reniérite)-ores (Intiomale and Oosterbosch, 1974). According to Hofmann and Henn (1984), this green colour is due to the presence of cobalt.

Pyrite composition is homogeneous in the different ore types (massive pyrite ores included), with a maximum As content of <0.5 wt.% at Kabwe and <2.5 wt.% at Kipushi. At Kipushi, arsenopyrite coexists with pyrite. According to Kamona (1993), the Co (average: 0.07 wt.%) and Ni (average: 0.02 wt.%) contents as well as the Co/Ni ratios (average: 3.96; range: 1.61–9.42) of pyrites from the Kabwe deposit are distinctly higher than the values documented in sedimentary pyrites (Co/Ni<1). They are similar to the values recorded by several workers (Loftus-Hills and Solomon, 1967; Cambel and Jarkovsky, 1968; Bralia et al., 1979; Campbell and Ethier, 1984) in pyrites from hydrothermal deposits. Microprobe analyses of pyrite from Kipushi indicate elevated Co (up to 1.2 wt.%) and low Ni (<0.02 wt.%) contents.

Galena is a major ore sulphide that nevertheless appears to have formed late in the paragenetic sequence. Composition of galena is uniform and, at Kabwe, its average content of Ag is 0.03 ± 0.01 wt.%. Chalcopyrite contains 0.19 to 0.33 wt.% Ge and the grains show exsolution intergrowths of briartite and reniérite (Kamona, 1993; Kamona and Friedrich, 2007). Both briartite and reniérite in the Kabwe massive sulphide ores contain inclusions of the other mineral, but homogeneous grains free of inclusions are also present. These rare briartite and reniérite grains occur as rounded to oval grains in pyrite, chalcopyrite, sphalerite and galena in the massive ores.

In the Kipushi deposit, briartite and reniérite occur in the mixed and Cu-rich ores (Intiomale, 1982), often associated with gallite, Ga-rich chalcopyrite and tungstenite. Sometimes briartite grains contain intergrowths of reniérite. Zn- and Fe-rich tennantite is an important carrier of Ag (up to 1.2 wt.% at Kipushi), and may also contain Ga (up to 0.9 wt.%) and Ge (up to 0.11 wt.%). Bornite is occasionally highly enriched in Ag (up to 9 wt.% in Kipushi), whereas tungstenite contains Cu, Ge (up to 2 wt.%), In (up to 1 wt.%) and Mo (<0.5 wt.%). Carrollite, stannoidite, germanocolusite, löllingite and scheelite have recently been identified as minor components of various sulphide ores at Kipushi (Melcher, unpublished data).

The composition of reniérite, germanite, briartite, gallite, Ga-rich chalcopyrite and germanocolusite from different deposits are shown in Table 3. Reniérite from Kabwe and Kipushi display identical Ge contents (ca. 8.3 wt.% on average) but Ga is commonly detected (up to 1.0 wt.%) at Kipushi whereas it is below detection limits at Kabwe. Briartites from Kipushi are also richer in As (up to 0.95 wt.%) and Cu (40–44 wt.%) than those from Kabwe (As: < mdl; Cu: 36–39 wt.%). Compared to Tsumeb, where germanite is the most abundant Ge phase, germanite is rare at Kipushi, and is commonly replaced by reniérite (De Vos et al., 1974; Intiomale and Oosterbosch, 1974). Germanocolusite was recently identified in drill core material from level 1150 at Kipushi, where it is intimately intergrown with reniérite and bornite; the mineral has previously been recognized as "Mineral Y" by Francotte (1962). Germanocolusite and Ge-bearing colusite are common accessory phases at Khusib Spings and Tsumeb, respectively (Spiridonov et al., 1992; Melcher, 2003; Melcher et al., 2006).

The mineral chemistry of mixed and Cu-rich ores from the Kipushi deposit is still poorly documented. Textural relationships show the complex evolution marked by resorptions, intergrowths, exsolutions of Cu and Zn–Pb minerals as well as Cu and Ge–Ga minerals in the mixed and Cu-rich ores (De Vos et al., 1974). These complex textural

Table 3
Composition of Ge- and Ga-minerals from Kipushi (source 1: De Vos et al., 1974; source 2: BGR, unpublished microprobe analyses), and Kabwe (source 3: Kamona, 1993; Kamona and Friedrich, 2007); data from Khusib Springs, Namibia, for comparison (source 4: Melcher et al., 2006).

Deposit	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kipushi	Kabwe	Khusib Springs	Khusib Springs
Minerals	Reniérite	Reniérite	Reniérite	Reniérite	Germanite	Briartite	Zn–briartite	Zn–briartite	Ga-briartite	Ga-briartite	Gallite	Gallite	Ga-Cpy	Ga-Cpy	Ga-Cpy	"Mineral Y"	Ge–colusite		Germanite	Ge–colusite
Source	1	2	2	2	1	1	2	1	1	2	1	2	1	2	2	1	2	3	4	4
Localisation		Level-787	Level-1150	Level-1270	Level-750	Level-750	Level-787	Level-753	Level-750	Level-787	Level-750	Level-787	Level-750	Level-787	Level-787	Level-775	Level-1150			(Range of 88)
Ag	–	–	0.12	0.06	–	–	–	–	–	–	–	–	–	–	–	–	0.07		0.04	≤ 2.4
As	0.95	0.13	0.55	2.00	–	0.07	0.16	0.04	0.10	0.17	–	–	–	–	–	1.14	0.87	<0.10	4.47	6.0–13.20
Cd		–	–	–			0.12			0.13		–		–	–	–	–			–
Cu	40.65	40.73	41.65	42.85	43.67	34.40	36.31	32.37	32.86	35.37	33.26	33.16	33.91	34.26	35.11	45.17	44.40	36–39	47.12	46.13–53.79
Fe	13.90	14.30	14.01	14.31	11.74	10.70	8.52	9.65	1.91	5.53	6.36	6.95	25.09	13.52	25.63	0.65	3.76		3.45	≤ 3.28
Ga	0.54	0.45	–	–	0.05	0.59	1.19	0.42	6.15	5.88	27.69	25.04	3.19	18.03	5.80	0.13	–		–	≤ 0.10
Ge	8.00	9.00	8.60	7.10	11.93	17.10	13.50	15.86	13.72	9.87	0.14	0.62	0.68	0.44	0.22	11.13	11.76	8.30	8.08	1.72–5.66
Mo	–	–	–	–	1.44	–	–	–	–	–	–	–	–	–	–	–	–		0.98	≤ 2.0
S	31.95	31.51	31.48	32.46	32.08	31.16	32.43	33.62	31.40	32.70	32.66	32.70	32.65	33.66	34.18	31.53	31.94		30.63	29.77–32.80
Sb	–	–	–	0.09	–	–	–	–	–	–	–	–	–	–	–	–	–		0.15	≤ 2.0
Se	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–		0.15	≤ 0.15
Sn	–	–	–	0.08	–	–	–	–	–	–	–	–	–	–	–	–	–			≤ 5.1
V	–	–	–	0.04	–	–	–	–	–	0.07	–	–	–	–	–	2.49	2.49		0.04	1.44–3.41
W	–	–	–	–	0.12	–	–	–	–	–	–	–	–	–	–	0.13	–		5.42	≤ 4.8
Zn	3.06	2.95	3.50	2.06	1.13	2.62	7.65	6.00	11.72	8.67	0.20	0.42	0.18	0.35	0.04	5.80	6.00		0.31	≤ 2.67
Total	99.05	99.07	99.91	101.05	102.16	97.44	99.87	97.96	97.86	98.38	100.31	98.89	95.70	100.26	100.98	98.32	101.29		100.84	

Ga–Cpy = gallium–chalcopyrite.

features result from the commingling of distinct mineralizing fluids (see next section). Several of these textures indicate relatively rapid precipitation of sulphides but also disequilibrium leading to extensive dissolution of previously deposited sulphides (Intiomale, 1982). In the Cu-rich orebody, bornite coexists with pyrite and chalcopyrite above 1300 m depth, and only chalcopyrite–pyrite persist at greater depths. In the Kipushi deposit, the primary bornite is silver-rich, in contrast with the secondary bornites from the supergene zone (<250 m depth) (Intiomale and Oosterbosch, 1974). Anderson (1975) showed that the stability fields for chalcopyrite (Cp), bornite (Bn) and pyrite (Py) in the presence of Zn–Pb minerals are highly controlled by oxidation state (log fO_2) and acidity (pH). According to experimentally derived solubility data, a mineral zonation marked by Cp + Py at depth and Cp + Bn + Py at shallow levels can be explained by an ascending mineralizing fluid undergoing a decrease in fO_2 and/or pH. However, ascending hot fluids would result in the decrease of temperature and increase of fO_2 during the crystallization of sulphide ores. The conversion of pyrite into iron oxides occurring in the collapse breccia in the Zn–Pb deposits in the Copperbelt is evidence of this increase of fO_2.

Ascending fluids resulted 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 (Intiomale, 1982). The vertical variation curves for Zn, Cu, Fe, 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 650 and 250 m), 2 (between 1200 and 650 m), and 3 (between 1200 and 1700 m), characterized by a vertical zonation of the metals with maximum values of Zn at the top and a Cu–Zn mixing 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) than at the top of the sequences (IM).

The Pb and Zn concentrations in barren Nguba Group dolomites (Pb<30 ppm; Zn<500 ppm) as well as in carbonates of the Roan Group (Pb ~ 50 ppm; Zn ~ 100 ppm) are generally low. Higher contents of up to 13,000 ppm Pb and up to 48,000 ppm Zn were recorded in mineralized dolomites in epigenetic dispersion haloes around the Kabwe deposit (Kamona, 1993). Hydrothermally-silicified rocks ("silicate ore" included), massive pyrite, Zn–Pb ores and Cu-rich ores in the Zn–Pb vein deposits at Kabwe contain less than 50 ppm Co. In Congo, all the Zn–Pb ores are also poor in Co, but up to 1000 ppm has been recorded in the Zn-rich, and 200–300 ppm in the Cu-rich (low Zn–Pb) ores hosted at the top of the Kakontwe Formation and in

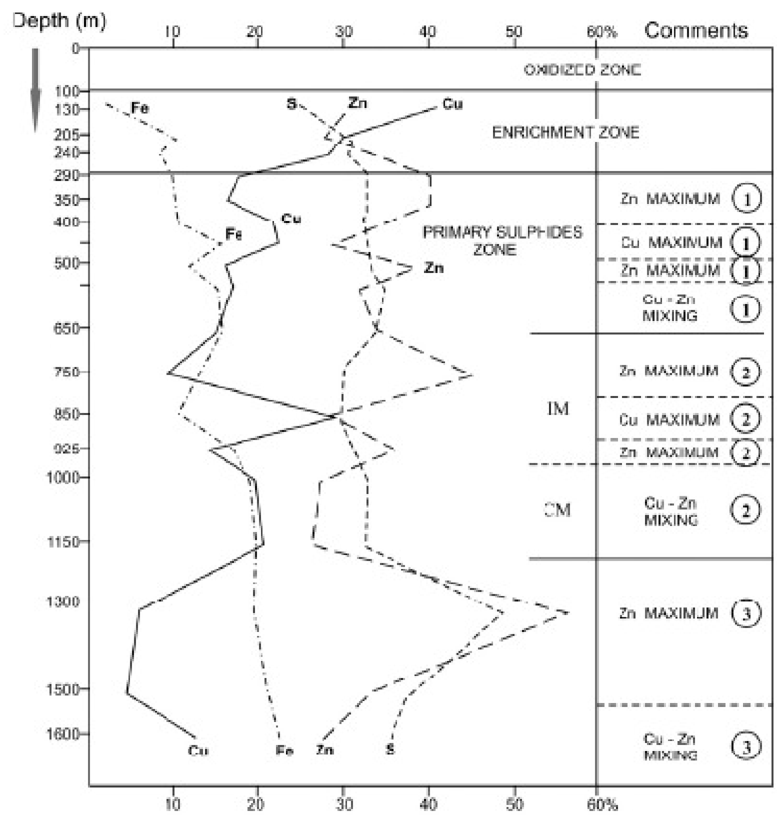

Fig. 19. Vertical variation curves for Zn, Cu, Fe, and S in the Cu-rich ore zone at Kipushi (modified from Intiomale, 1982). IM: incomplete mixing; CM: complete mixing.

Table 4
Composition of the Nguba carbonates from Kipushi (Laboratoire de Minéralogie et Géologie Appliquée, Université Catholique de Louvain, Belgique, for major and minor elements; Ecole Nationale Supérieure de Géologie Appliquée de Nancy, France, for trace elements), Kengere, Lombe and Kabwe (Laboratoire Etudes Métallurgiques de Likasi, Gécamines, Congo) (Intiomale, 1982).

Deposit	Kipushi	Kipushi	Kipushi	Kipushi	Kengere	Kengere	Kengere	Lombe	Lombe	Kabwe	Kabwe
Formation	Kaponda	Kaponda	Kakontwe	Kipushi	Kaponda	Kakontwe	Kipushi	Kipushi	Katete (SR)	Kaponda	Kakontwe
Lithology	"Dolomie Tigrée"	Carbonates	Carbonates	Carbonates	Carbonates	Carbonates	Carbonates	Carbonates	Carbonates	Carbonates	Carbonates
Major and minor elements (wt.%)											
SiO_2	1.45	3.17–60.05	1.15–19.19	17.84–43.52	1.60–4.68	1.98–2.70	2.90	0.64–6.48	6.68–53.00	2.00–40.00	2.00–5.00
Al_2O_3	0.53	0.12–19.53	0.09–2.03	1.43–9.60	0.13–0.20	0.16–0.19	0.15	0.08–0.13	0.12–0.13	0.20–5.40	0.20–0.30
Fe_2O_3	2.67	0.34–7.10	0.44–1.00	1.13–5.83	–	–	–	–	–	0.19–4.26	0.15–3.12
MgO	19.95	4.21–21.50	18.19–22.1	21.54–27.39	5.19–13.42	5.02–5.16	5.30	6.32–13.96	9.06–17.15	9.00–23.00	19.00–23.00
CaO	30.26	0.34–41.45	23.01–31.26	0.86–22.19	39.52–48.16	48.47–49.07	48.06	35.31–47.49	12.85–30.09	12.00–31.00	28.00–31.00
MnO	–	–	–	–	–	–	–	–	–	0.08–0.30	0.07–0.13
Na_2O	0.22	0.02–0.17	0.08–0.66	0.08–0.09	–	–	–	–	–	0.03–0.15	0.04–0.18
K_2O	0.13	0.04–2.26	0.04–0.54	0.09–0.57	–	–	–	–	–	0.02–3.48	0.04–0.15
P_2O_5	–	–	–	–	–	–	–	–	–	0.02–0.90	0.03–0.12
TiO_2	0.04	0.01–1.73	0.01–0.11	0.08–1.86	–	–	–	–	–	0.01–0.22	0.01–0.09
LOI	44.37	5.49–44.11	33.39–44.19	9.23–34.04	–	–	–	–	–	–	–
Trace elements (ppm)											
Ba	–	–	10	103–125	–	–	–	–	–	–	–
Co	–	–	32	17–20	–	–	–	–	–	–	–
Cr	–	–	113	82–105	–	–	–	–	–	–	–
Cu	–	–	<10	<10	–	–	–	–	–	–	–
Ni	–	–	427	193–373	–	–	–	–	–	–	–
Sr	–	–	111	193–341	–	–	–	–	–	–	–
Cl	–	–	72	220–225	–	–	–	–	–	–	–
V	–	–	23	17–68	–	–	–	–	–	–	–
Rb	–	–	<10	17–26	–	–	–	–	–	–	–

the Katete Formation at Kipushi (Intiomale and Oosterbosch, 1974; BGR, unpublished data). In contrast, the stratiform copper deposits of the Roan Group contain high grades of cobalt, i.e., 0.33 and 0,04 wt.% Co, on average, respectively in the Congo-type and Zambia-type facies, with a maximum of 2.59 and 0.18 wt.% Co, respectively (Cailteux et al., 2005b). Gold shows significant values in the Congo-type stratiform Roan Group deposits whereas silver is important in Zambia-type deposits. At Kipushi, up to 123 ppb Au were recently analysed 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 dolomitic composition, with 4.2 wt.%<MgO<27.4 wt.% and 0.3 wt.%<CaO<49.1 wt.% (Table 4), while thick limestone beds (1.0 wt.%<MgO<4.3 wt.% and 42.8 wt.%<CaO<54.2 wt.%) alternating with dolomites occur in other sites (e.g., Lufunfu, south of Kolwezi; Tantara in the Shinkolobwe area; Kakontwe in the Likasi area; Table 5). High contents of MgO (4.2–10.2 wt.%) are also common in the Nguba Group dolomitic shales associated with the carbonates in the Zn–Pb deposits (Intiomale, 1982). Similarly, the Roan Group is characterized by MgO-rich rocks, a feature that Moine et al. (1986) attributed to pre-metamorphic magnesian clay minerals in evaporitic sequences. The values of MgO and TiO_2 (generally > 1 wt.%, up to ca. 2 wt.%) in the Nguba Group shales are generally higher than the averages (3.3 wt.% MgO, 0.78 wt.% TiO_2) in platform shales (Carmichael, 1989). However, similar dolomitic shales associated with dolomites are known in several platform deposits hosting Mississippi Valley-type Zn–Pb deposits.

The host rocks and the gangue minerals in the low grade metamorphic zone commonly include carbonates, quartz, muscovite, chlorite, phlogopite, albite, K-feldspar and barite. Talc occurs only in the barren rocks (Chabu, 1990) and, as common for this mineral (Bucher and Frey, 1994), very little iron is substituted for magnesium (Fe<0.07 a.p.f.u. at Kipushi). Phlogopite is F- and Mg-rich with 4.4 wt.%< F<6.4 wt.% in the sulphide-bearing assemblages and F–Mg poor (<1 wt.% F) in the barren rocks. Evaporitic country rocks contain phlogopites with the same Mg contents as those from the ores, but are also distinctly lower (<2 wt.%) in fluorine.

Chlorites are Mg-rich (Mg/(Mg + Fe) up to 0.8) in the country rocks whereas they are Fe-rich (Mg/(Mg + Fe) down to 0.3) in Zn–Pb ores. This suggests that the ore fluids were marked by higher X_{Fe} values than fluids in the barren rocks. Talc is not in equilibrium in such chemical environments and this in turn explains the absence of this mineral in mineralized dolomites. Mg-chlorite, phlogopite and talc are generally recorded in shales and shaly dolomites at several lithostratigraphic 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 and Boulègue (1992) have reported Ba-rich muscovites (up to 7.7% BaO) coexisting with (Ba–K) feldspars with 1.5%<celsian content <85% (adularia–hyalophane–celsian) and barites in the gangue assemblage. No microprobe analyses are available on white micas occurring in assemblages containing talc + kyanite in the Semahwa Zn occurrence. At Kabwe, the composition of dolomite is quite similar in the fine grains of the country rocks, and in the coarse porphyroblastic and vein related grains, except that significant contents of Zn (up to 0.4 wt.%) and Pb (up to 0.2 wt.%) occur only in dolomites close to the orebodies (Kamona, 1993).

5. Mineral geothermometry

The mineral assemblages in the host rocks at Kipushi and Kabwe reflect greenschist facies metamorphic conditions as indicated by talc +

Table 5
Major elements composition of Kakontwe carbonates from unmineralized sites (François, 1973a).

Site	Kakontwe	Kakontwe	Tantara	Tantara	Lufunfu
Formation	Kakontwe	Kakontwe	Kakontwe	Kakontwe	Kakontwe
Lithology	Dolomites	Limestones	Dolomites	Limestones	Limestones
Thickness (m)	43	200	390	170	?
Al_2O_3 + SiO + Fe_2O_3	–	–	1.75–7.33	2.95–3.98	–
MgO	12.24–19.33	1.01–3.27	13.08–19.08	4.18–4.28	1.70
CaO	29.37–40.47	46.59–54.15	27.63–34.11	42.79–47.52	52.30

chlorite + albite, and the absence of tremolite in dolomites and dolomitic shales. Talc in dolomites of orogenic belts is usually associated with hydrothermal activity and its stability in the low pressure regimes of ca. 2 ± 1 kbar postulated for the Lufilian metamorphism (Cluzel, 1986) implies temperatures below 450 °C (Bucher and Frey, 1994). K-feldspar (Kfs) coexists in equilibrium with phlogopite (Phl), muscovite (Ms), chlorite (Chl), talc (Tlc) and quartz (Qz) in these Al-poor rocks. The dolomitic shales crystallized around the univariant curve of the reaction 8Kfs + 3Chl = 3Ms + 5Phl + 9Qz + 4H_2O which is restricted to ca. 410–430 °C at a pressure of 3.5 kbar (Bucher and Frey, 1994). The assemblage talc + kyanite at the Semahwa Zn occurrence marks a high pressure regime and temperatures bracketed between 550 °C at 16 kbar and 700 °C at ca. 9 kbar.

Sphalerite geothermometry used on the Zn-rich ore pipes at Kipushi suggests temperatures of formation between 305 and 380 °C (Ottenburgs, 1964). The occurrence of exsolution intergrowths between chalcopyrite, briartite and reniérite at both Kabwe and Kipushi indicate cogenetic formation of these minerals from a high-temperature parent Cu–Ge–Fe–S solid solution (Kamona and Friedrich, 2007). According to Takeno (1975), the β-low-temperature polymorph of chalcopyrite may contain up to 4 wt.% briartite in solid solution at 480 °C.

Sulphur isotopic fractionation between pyrite, sphalerite and galena, coexisting in apparent equilibrium at Kabwe, yielded an isotopic temperature of 290 ± 35 °C (Kamona and Friedrich, 2007). Generally, the isotopic enrichment in sulphides follows the equilibrium fractionation trend pyrite > sphalerite > galena, but the isotopic temperatures given by the sulphide pairs are variable. The sphalerite–pyrite geothermometer yielded values in the range 140°–370 °C with a mean isotopic fractionation defining an isotherm of 262 ± 29 °C (Kamona and Friedrich, 2007). In contrast, coexisting pyrite–galena (250–550 °C) and sphalerite–galena (290–540 °C) sulphide pairs both exhibit apparent disequilibrium conditions due to the generally late paragenetic position of galena (Kamona, 1993; Kamona and Friedrich, 2007).

6. Fluid inclusions studies

Fluid inclusions investigated in the Zn–Pb deposits of Kabwe and Kipushi display strong similarities. At Kabwe (Kamona and Friedrich, 2007), fluid inclusions in sphalerite, quartz and dolomite associated with massive sulphide ores, vein mineralization and the wallrock dolomite characterized by liquid + vapour + solid (L + S + V) and liquid + vapour (L + V) phases were identified as high-temperature fluids (HTF) and low temperature fluids (LTF), respectively. The range of homogenization temperatures (T_h) recorded in HTF inclusions is 250–390 °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 Kipushi (Heijlen et al., 2007a, 2008), fluid inclusions in dolomites and quartz associated with the main stage of sulphide mineralization, showing L + S + V phases, indicate a range of temperatures between 221 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) in intergranular trails in dolomite and quartz crystals, and in late stage sphalerite, indicate temperatures in the range <80–170 °C and salinities between 23 and 31 wt.% NaCl equivalent.

At Dikulushi, two fluids were identified by fluid inclusion analysis in sphalerite, dolomite, quartz, barite and calcite (Dewaele et al., 2006; Haest et al., 2007a): (1) a high-salinity fluid (20.7–24.4 wt.% $CaCl_2$ equivalent) in inclusions with L + V phases (H_2O–$CaCl_2$–NaCl composition) indicating temperatures between 125 and 185 °C and related to the first generation sulphides; (2) a second type fluid with lower salinities (2.94–12.53 wt.% NaCl equivalent; inclusions with L + V or only L phases) and temperatures around 70 °C, related to the late dominantly chalcocite mineralization.

Table 5
Comparison between Dikulushi, Kansanshi, Kipushi, Kabwe, Tsumeb, Khusib Springs, and Berg Aukas Zn–Cu–Pb type deposits for main sulphides minerals, ore chemistry, sulphur range isotope ratios of sulphides, carbon and oxygen range isotope ratios of dolomite, salinites and temperatures of high and low-temperature fluid inclusions (Dechow and Jensen, 1965; Dewaele et al., 2006; Melcher et al., 2006; Haest et al., 2007a; Heijlen et al., 2007, 2008; Kamona and Friedrich, 2007).

Deposit	Dikulushi	Kansanshi	Kipushi	Kabwe	Tsumeb	Khusib Springs	Berg Aukas
Orebodies	Breccia + fracture zones in Kundelungu sandstones	Veins + stratabound in Nguba carbonates	Discordant pipes in Nguba carbonates and breccia + stratiform in hangingwall		Discordant pipe + breccia and sandstone	Stratiform lens + dolomite breccia	Stratiform lenses + discordant breccias
Main sulphides	[1] Sph, Cp, Bn, Cc, Apy, Py, Tn, Gal [2] Cc	Cp Bn	Sph, Cp, Bn, Cc, Py, Apy, Tn, Gal	Sph, Gal, Py, Cp	Tn, Gal, Sph, Py, Bn, Cp	Tn, En, Gal, Sph, Py	Sph, Gal
Orechemistry	[1] Zn, Pb, Fe, Cu, As [2] Cu–Ag	Cu Au, Mo, Ag	Zn, Cu, Pb, Fe, Cd, Co, Ge, Ag, Re	Zn, Pb, Ag, V, Cu, Cd, Ge, Ga, In	Pb, Cu, Zn, As, Ag, Cd, Ge, Ga, W	Cu, Pb, Zn, As, Sb, Ag, Ge, Cd, Hg	Zn, Pb, V
$\delta^{34}S$			−2.6 to +19.2‰		+13.1 to +26.6‰	+20.8 to +27.8‰	+17 to +30‰
Massive ore			> +12.0‰	−18.73 to −10.80‰			
Disseminated ore			−5.7 to +2.0‰	−14.80 to −12.30‰			
Disseminated pyrite				−7.50 to −5.10			
$\delta^{13}C_{PDB}$ dolomite				+0.87 to +3.18‰	−7 to +2‰	−4 to +1‰	+3 to +5‰
$\delta^{18}O_{SMOW}$ dolomite				+26.41 to 28.81‰	+18 to +21‰	+17.3 to +20.4‰	
High Tp fluid inclusions	[1]						
Salinities	20.7–24.4 equivalent wt.% $CaCl_2$		30–43 equivalent wt.% NaCl	<31 equivalent wt.% NaCl	22 ± 3 equivalent wt.% NaCl	20 ± 4 equivalent wt.% NaCl	± 23 equivalent wt.% NaCl
Homogenization Tp	125–185 °C		221–339 °C	250-390 °C	212-275 °C	291–370 °C	137–255 °C
Low Tp fluid inclusions	[2]						
Salinities	2.9–12.5 equivalent wt.% NaCl		23–31 equivalent wt.% NaCl	± 11.5 equivalent wt.% NaCl			
Homogenization Tp	46–82 °C		<80–170 °C	80–180 °C			
Age	<600 Ma	513–502 ± 1.2 Ma	451 ± 6 Ma	680 ± 13 Ma	530 to 460 Ma ?	Unknown	750 to 635 Ma ?

Abbreviations (main sulphides): Apy: arsenopyrite; Bn: bornite; Cc: chalcocite; Cp: chalcopyrite; En: enargite; Gal: galena; Py: pyrite; Sph: sphalerite; Tn: tennantite.

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 Musoshi, Richards et al. (1988a) recorded bimodal populations in fluid inclusions from quartz (+ hematite) veins similar to the Zn–Pb deposits. The HTF population is marked by values between 342 and 375 °C whereas the LTF population has temperatures ranging between 195 and 229 °C. The salinity is also higher in the HTF population (minimum: 39 wt.% NaCl + 15 wt.% KCl) and lower in the LTF population (28 wt.% NaCl + 17 wt.% KCl). At Luiswishi (in Congo) and Chambishi (in Zambia), the distribution of T_h values of fluid inclusions in late stage veins and in the tectonic breccia cement are between 197 and 439 °C, while salinities are between 22 and 46.5 wt.% NaCl equivalent (Annels, 1989; Greyling et al., 2005; Dewaele et al., 2006; El Desouky et al., 2007, 2008). These values are typically higher than T_h and salinities measured in authigenic quartz and dolomite associated with the early diagenetic Cu–Co mineralization at Chambishi, Kamoto-Principal and Musonoï (Kolwezi area, Congo) recording primary salinities in the sediments (Pirmolin, 1970; Ngongo, 1975; Audeoud, 1982; Annels, 1989; Greyling et al., 2005; El Desouky et al., 2007, 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 vs. salinity is plotted in Fig. 20. They are compared to data from Namibian Zn–Pb deposits (Berg Aukas, Tsumeb, Khusib Springs) that show Th and salinities values in the range of 137–370 °C and 20–23 wt.% NaCl equivalent, respectively (Chetty and Frimmel, 2000).

7. Isotope studies

7.1. Lead isotopes

In the past, a number of Pb isotopic analyses have been performed on sulphides, gangue carbonates and host rocks in the Zn–Pb Katangan deposits (Walraven and Chabu, 1994; Kamona et al., 1999). The data are summarised in Table 8 and plotted on ($^{207}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$) and ($^{208}Pb/^{204}Pb$ vs. $^{206}Pb/^{204}Pb$) diagrams (Fig. 21a, b). All sulphides from the Zn–Pb orebodies in Congo and in Zambia show small variations in their Pb isotopic compositions within the following ranges: $^{206}Pb/^{204}Pb$ = 17.72–18.63; $^{207}Pb/^{204}Pb$ = 15.50–15.73 and $^{208}Pb/^{204}Pb$ = 37.25–38.46. Such values are typical of the upper continental crust (Kamona et al., 1999).

The ranges of lead isotopes for dolomite host rocks show values close to those of the sulphides ($^{206}Pb/^{204}Pb$ = 17.90–19.72; $^{207}Pb/^{204}Pb$ = 15.47–15.72 and $^{208}Pb/^{204}Pb$ = 37.23–38.37), while the ranges for the intrusive gabbro in the fault breccia are divergent (Table 8; Fig. 21c, d). Lead isotope compositions of the Zn–Pb ores hosted in carbonates of the Otavi Group in the Damara belt (Table 8; Fig. 21a, b) are also similar to those documented in the Zn–Pb deposits in the Copperbelt of Central Africa (Hughes et al., 1984; Kamona et al.,

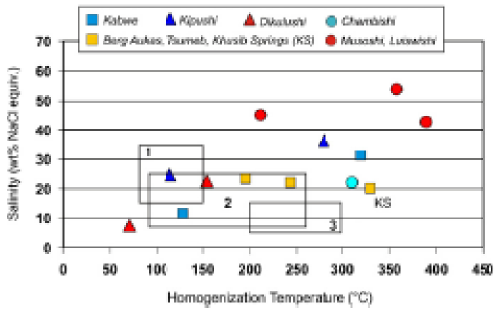

Fig. 20. Homogenization temperatures and salinity mainly from sphalerite, quartz, and dolomite associated with the mineralization from Kabwe, Kipushi and Dikulushi deposits; comparison with Zn–Pb deposits in Namibia (Berg Aukas, Tsumeb, and Khusib Springs) and with veins or tectonic breccia cement from Cu–Co deposits in the Central African Copperbelt (Chambishi, Musoshi, and Luiswishi). Comparison with ranges of classical models for (1) Mississipi Valley type (MVT); (2) Irish type; and (3) SEDEX type (Goodfellow et al., 1993; Hitzman, 1995).

Table 7
Comparison between Kamoto-Principal + Musonoï (Kolwezi area), Luiswishi, Musoshi, and Chambishi (Zambia) stratiform Cu–Co deposits in the Copperbelt (Richards et al., 1988a; Annels, 1989; Greyling et al., 2005; Selley et al., 2005; Dewaele et al., 2006; El Desouky et al., 2007, 2008).

Deposit	Kamoto-Principal and Musonoï (Kolwezi area)	Luiswishi	Musoshi	Chambishi (Zambia)
High Tp fluid inclusions in veins and breccia				
Salinities	35.3–41.5 wt.% NaCl equivalent	38.6–47.0 wt.% NaCl equivalent	39 wt.% NaCl; 15 wt.% KCl	22 ± 3 wt.% NaCl equivalent
Homogenization Tp	270–365 °C	300–439 °C	342–375 °C	197–425 °C
Age		600–512 Ma	514 ± 3 Ma	?
Low Tp fluid inclusions in veins				
Salinities			28 wt.% NaCl; 17 wt.% KCl	
Homogenization Tp			195–229 °C	
Age			514 ± 3 Ma	
Fluid inclusions in sedimentary rocks				
Salinities	8.4–20.9 wt.% NaCl equivalent			11.0–23.1 wt.% NaCl equivalent
Homogenization Tp	80–220 °C			86–180 °C
Age				816 ± 62 Ma

Table 8
Ranges of the lead isotope ratios for sulphides from Zn–Pb–Cu deposits at Kipushi, Lombe, and Kengere (Walraven and Chabu, 1994), Kabwe and Tsumeb (Kamona et al., 1999), from Cu–Co stratiform deposits at Kolwezi, Kinsenda and Musoshi (Richards et al., 1988b; Walraven and Chabu, 1994), and for intrusive gabbro blocs from the Kipushi fault breccia (Walraven and Chabu, 1994).

Deposit	$^{206}/^{204}Pb$	$^{207}/^{204}Pb$	$^{208}/^{204}Pb$
Kipushi			
Galena	18.000–18.221	15.596–15.653	37.533–37.961
Other sulphides	17.721–18.096	15.496–15.718	37.252–37.963
Dolomite host rock	17.904–19.717	15.564–15.714	37.474–37.877
Gabbro intrusive	19.285–26.225	15.682–16.111	38.907–42.170
Lombe			
Galena	–	–	–
Other sulphides	18.044–18.626	15.593–15.619	37.504–37.793
Dolomite host rock	17.921–18.183	15.473–15.604	37.228–37.583
Kengere			
Galena	–	–	–
Other sulphides	18.017–18.052	15.598–15.620	37.511–37.710
Dolomite host rock	–	–	–
Kabwe			
Galena	17.978–18.008	15.688–15.728	38.329–38.458
Other sulphides	–	–	–
Dolomite host rock	17.982–18.017	15.685–15.722	38.280–38.370
Tsumeb			
Galena	18.094–18.144	15.667–15.688	38.248–38.345
Other sulphides	–	–	–
Dolomite host rock	–	–	–
Kolwezi (Mines group stratiform orebodies)			
Cu-sulphides	18.590–19.207	15.704–15.779	38.077–38.390
Dolomite host rock	18.174	15.621	37.697
Kinsenda (Mindola group stratiform medium ore zone orebody)			
Cu-sulphides	17.642–17.796	15.337–15.655	36.583–37.849
Dolomite host rock	17.893–18.073	15.553–15.617	38.536–39.501
Musoshi (Kitwe Subgroup ore shale orebody)			
Stratiform Cu-sulphides	18.630–97.638	15.724–20.444	40.640–140.550
Vein-sulphides	19.948–32.633	15.802–16.474	43.197–47.448

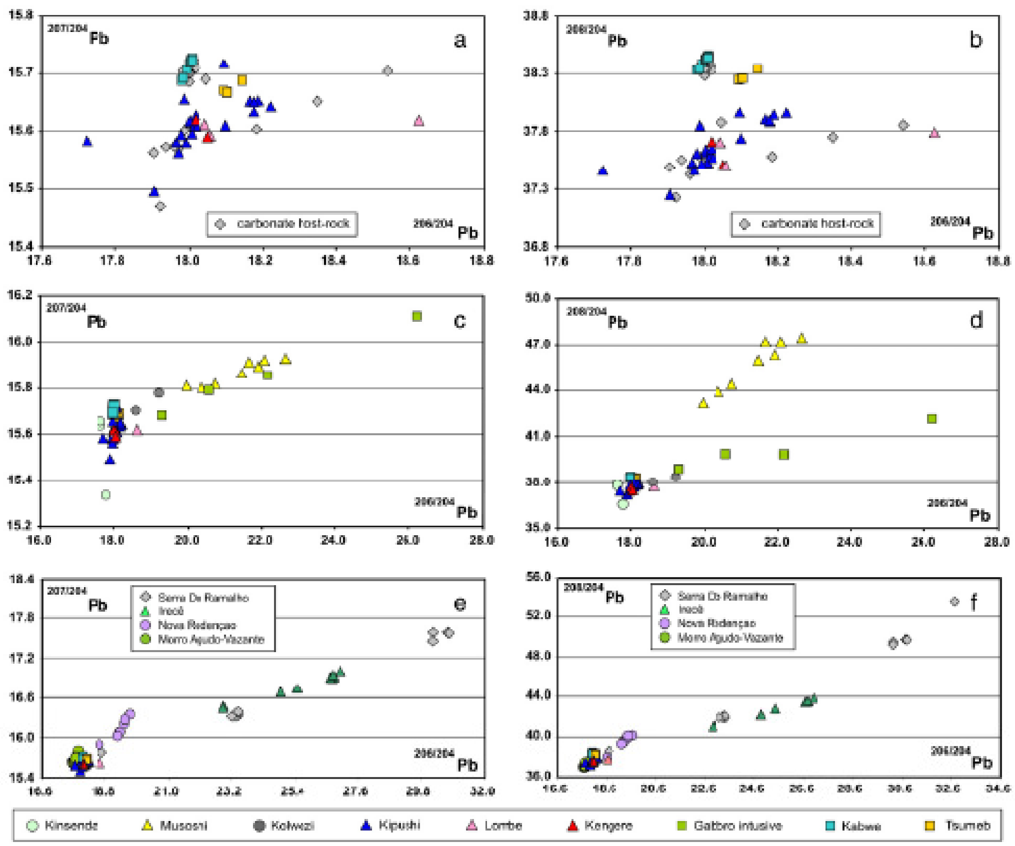

Fig. 21. (a) $^{206/204}$Pb vs. $^{207/204}$Pb and (b) $^{206/204}$Pb vs. $^{208/204}$Pb diagrams for sulphides and host rocks from Zn–Pb–Cu deposits at Kipushi, Lombe, and Kengere (Walraven and Chabu, 1994), Kabwe and Tsumeb (Kamona et al., 1999); (c) $^{206/204}$Pb vs. $^{207/204}$Pb and (d) $^{206/204}$Pb vs. $^{208/204}$Pb diagrams for sulphides from Zn–Pb–Cu deposits at Kipushi, Lombe, and Kengere (Walraven and Chabu, 1994), Kabwe and Tsumeb (Kamona et al., 1999), compared to those from Cu–Co stratiform deposits at Kolwezi and Kinsenda (Walraven and Chabu, 1994), intrusive gabbro blocs from the Kipushi fault breccia (Walraven and Chabu, 1994), and veins sulphides at Musoshi (Richards et al., 1988b); (e) $^{206/204}$Pb versus $^{207/204}$Pb and (f) $^{206/204}$Pb versus $^{208/204}$Pb diagrams for sulphides from Zn–Pb–Cu deposits at Irecê, Nova Redenção, Serra do Ramalho, and Morro Agudo/Vazante (Misi et al., 2005) compared to those from the Central Africa and Namibian deposits.

1999). Such restricted variations for Zn–Pb ore deposits at the southern margin of the Congo craton suggest that these deposits may have the same metal sources, namely the upper continental crust.

By contrast, sulphides from the stratiform orebodies of the Roan Group (e.g., at Kolwezi, Kinsenda, and Musoshi; Table 8, Fig. 21c, d) are marked by significant variation in lead isotopic compositions, from low values similar to those documented in Zn–Pb deposits up to more radiogenic composition: $^{206}Pb/^{204}Pb = 17.64–97.64$; $^{207}Pb/^{204}Pb = 15.34–20.44$ and $^{208}Pb/^{204}Pb = 36.58–140.55$ (Richards et al., 1988b; Walraven and Chabu, 1994). Recent lithostratigraphic studies (Cailteux et al., 1994, 1995) have shown that the main copper deposits are hosted by correlative lithostratigraphic units in Congo (Mines Subgroup) and in Zambia, (Kitwe Formation) and it seems improbable that the age difference would be sufficient to explain the large variation of Pb isotopic composition within the stratiform Cu–Co sulphides and between the stratiform Cu orebodies and the stratabound Zn–Pb deposits. Thus, one must seek the major cause for heterogeneities in the lead sources.

The range of lead isotopes in the Palaeoproterozoic calc-alkaline rocks in the Copperbelt (Mufulira granodiorite) and in the Bangweulu block (Pepa-Lubumba) is relatively limited with $^{206}Pb/^{204}Pb = 17.16–20.73$; $^{207}Pb/^{204}Pb = 15.52–15.96$ 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 sulphides from the Neoproterozoic ore deposits. The calculations show that, at around 700 Ma, the lead isotope ratios of these calc-alkaline rocks were similar to that of the least radiogenic sulphides in the stratiform copper deposits and that of the Zn–Pb ores, i.e., $^{206}Pb/^{204}Pb \sim 18.1$, $^{207}Pb/^{204}Pb \sim 15.6$ and $^{208}Pb/^{204}Pb \sim 37.9$.

Comparison of the Pb isotopic sulphide values from the Central Africa and Namibian Zn–Pb deposits with isotopic ratios from several Zn–Pb deposits of the Neoproterozoic Bambui Group and correlative sequences of the São Francisco Craton in Brazil shows that the Morro Agudo, Vazante, and Nova Redenção deposits ($^{206}Pb/^{204}Pb = 17.61–19.67$; $^{207}Pb/^{204}Pb = 15.56–16.34$ and $^{208}Pb/^{204}Pb = 36.89–40.13$; Misi et al., 2005) have similar isotopic ratios. In contrast, the other Zn–Pb deposits (Irecê, Serra Do Ramalho) have very different ranges of isotopic ratios (Fig. 21e, f).

7.2. Stable isotopes

Sulphur isotope variations, in terms of conventional permil deviation ($\delta^{34}S$ ‰) relative to the Canyon Diablo Troilite (CDT), are shown in Table 6. The $\delta^{34}S$ values for the Kipushi deposit show the greatest spread from −2.6 to +19.2‰ (Dechow and Jensen, 1965) which is in marked contrast to the more homogeneous isotopic ratios of massive sulphides at Kabwe (−10.2 to −18.7‰) (Kamona and Friedrich, 2007). At Kipushi, the discordant massive sulphide orebodies in dolostones of the Kakontwe Formation, the main host rock, have relatively heavy $\delta^{34}S$ values from +12.8 to +19.2‰ with an average value of +15.1 ± 1.8 ($n = 10$, Dechow and Jensen, 1965). In contrast, sulphides in the sub-concordant orebodies in dolomitic shale and dolomite of the Katete Formation have the largest spread from −2.6 to +18.0‰ ($n = 9$), whereas the barren dolomitic shales of Nguba rocks overlying the mineralized horizon have more uniform and lighter $\delta^{34}S$ values between −5.7 and +2.0‰ ($n = 8$, average = −2.5 ± 2.8; Dechow and Jensen, 1965).

Isotopic ratios of sulphides from other Zn–Pb deposits for which data is available (Millberg−6.1 to −14.0‰ and Itawa−11.3 to −16.4‰; Dechow and Jensen, 1965) have $\delta^{34}S$ values comparable to those found at Kabwe. Such negative $\delta^{34}S$ values with narrow spreads are characteristic of sedimentary sulphides produced through bacterial reduction of seawater sulphate (Kamona and Friedrich, 2007). The negative $\delta^{34}S$ values in the Kipushi deposit are possibly from diagenetic pyrites, whereas the much heavier isotope ratios of +15.1‰ in the Kakontwe limestone and up to +18.0‰ in the Katete Formation, are close to the average isotopic ratio of +17.5‰ for Neoproterozoic seawater sulphate on the Copperbelt (Dechow and Jensen, 1965; Claypool et al., 1980).

In comparison, the $\delta^{34}S$ values of igneous metabasic rocks intruding the Dipeta/Kirilabombwe subgroups in the Copperbelt range from +1.0 to +15.7‰ (Dechow and Jensen, 1965). Sulphur isotope ratios in fresh basic rocks generally differ little from meteorites (around 0‰). The high fractionation (ca. 15‰) and the high values of $\delta^{34}S$ recorded in some of the metabasic rocks cannot be attributed to isochemical metamorphic processes that are generally thought to preserve sulphur isotopic compositions (Rye and Ohmoto, 1974; Ohmoto, 1986; O'Neil, 1986; Crowe, 1994). It is therefore likely that the heavy $\delta^{34}S$ values were assimilated from the country rocks during the intrusion of the gabbroic rocks at around 760 Ma. The country rocks are characterized by heavy sulphur isotopes of +17.5‰, whose ultimate source was seawater sulphate.

The $\delta^{34}S$ for Cu-sulphides from the stratiform Cu–Co deposits in the Roan Group are broadly similar in both the Congolese facies (−9.8 to +18.7‰) and in the Zambian facies (−8.7 to +13.0‰) of the Copperbelt (Cailteux et al., 2005b and references therein). This wide spread of sulphur isotope ratios probably indicates involvement of both diagenetic sulphides and seawater sulphate in the ore-forming processes of these stratiform deposits.

Carbon and oxygen isotope compositions are available only for the Kabwe deposit where the dolomite host rocks have $\delta^{13}C_{PDB}$ (2.89‰) and $\delta^{18}O_{SMOW}$ (27.68‰) values typical of marine carbonates (Kamona and Friedrich, 2007). The $\delta^{18}O$ and $\delta^{13}C$ values in the Kabwe mineralized dolomite define an isotopic depletion trend related to increasing silica content in the host dolomite due to wallrock silicification.

8. Age constraints on the deposits

Late Ordovician ages of 451.1 ± 6 Ma and 450.5 ± 3,4 Ma were obtained for Kipushi by direct Rb–Sr and Re–Os dating of sulphides from two drill cores, respectively (Schneider et al., 2007). The 454 ± 14 Ma ($\mu = 9.88$) lead model age of (Walraven and Chabu, 1994), based on the Stacey and Kramers (1975) crustal evolution curve, is consistent with the post-tectonic 451 Ma age of the Kipushi deposit. The 451 Ma of the Kipushi deposit may be related to the magmatic emplacement of post-tectonic hypabissal syenite intrusions dated at 458 to 427 Ma (U–Pb zircon ages) in the Domes area (Cosi et al., 1992).

The Kansanshi Cu-Au deposit in the Domes area is the only other post-tectonic deposit to have been dated using the precise Re–Os method on molybdenite, indicating that vein mineralization occurred at ~512 and ~502 ± 1.2 Ma (Torrealday et al., 2000). In the case of Kabwe, Pb isotopic compositions of ore galena have been used to suggest a model age of 680 ± 13 Ma ($\mu = 10.31$) based on the Stacey and Kramers (1975) model with reference to the lead isotopic framework of crustal rocks in the Lufilian Arc (Kamona et al., 1999). Cahen (1974) suggested a Pb model age of 600 Ma for the Kengere Zn–Pb deposit as well as for the lead occurrences at Mulungwishi.

Stratigraphic age constraints provided by recent robust U–Pb age data on zircons from the Lufilian Belt (Key et al., 2001; Barron et al., 2003; Armstrong et al., 2005; Master et al., 2005; Rainaud et al., 2005b) indicate that the Roan Group was deposited from ca. 880 to 735 Ma. This age range is useful in bracketing the age of the syndiagenetic stratiform Cu–Co ores in the Copperbelt which are concentrated in the lower parts of the Roan Group. The 735 Ma age provides a maximum age limit for any epigenetic deposits in the Roan Group, including the Kabwe deposit.

The age of the Nguba Group may be bracketed between 735 and 635 Ma, which represent the respective ages of mafic volcanics at the base of the glaciogenic Grand Conglomérat (Key et al., 2001) and the presumed age of the Petit Conglomérat, respectively. The age of the Petit Conglomérat given in this paper is based on lithostratigraphic correlation of the Petit Conglomérat with the glaciogenic Ghaub Formation in Namibia which has a U–Pb zircon age of 635.5 ± 1.2 Ma (Hoffmann et al., 2004). The 635 Ma age may be considered as the maximum age limit of any epigenetic deposit in the Nguba Group, including the Kipushi deposit.

Observed deformation features such as flattening of the ores, development of pressure shadows, bent cleavages and ore brecciation (Chabu, 1990; Kamona and Friedrich, 2007), indicate that the Zn–Pb ore deposits may have been affected by tectonic deformation during any one of the three phases of the Lufilian Orogeny between ca. 750 and 512 Ma. The occurrence of most Zn–Pb deposits (Kipushi, Kabwe, Kengere and Lombe) along NE–SW trending D2 faults cutting across earlier NW–SE trending-folds and thrusts (Kampunzu and Cailteux, 1999) indicates that mineralization may be post-tectonic with respect to the D_1 Kolwezian phase of the Lufilian Orogeny.

As discussed above (see geological background), the Kolwezian orogenic phase is associated with plate convergence and subduction from ca. 750 to 600 Ma. The D_2 Monwezian phase of the Lufilian Orogeny probably occurred between 603 and 512 Ma as indicated by recent U–Pb dating of metamorphic monazite in the Copperbelt (Lerouge et al., 2004; Rainaud et al., 2005b). In the case of the Kabwe deposit, the NE–SW fault system probably represents reactivated basement faults (De Swardt et al., 1965). Both the NE–SW faults and the Kabwe orebodies terminate at the younger Mine Club Fault (Kamona and Friedrich, 2007; Figs. 16 and 17) which is associated with tectonic uplift at 528 Ma in central Zambia (Barr et al., 1978).

According to Chabu (1990) and Chabu and Boulègue (1992), the Kipushi deposit is characterized by mineral assemblages of the greenschist facies, including barian muscovite and (Ba, K)-feldspar of metamorphic origin. The Kabwe deposit also experienced a phase of low grade greenschist metamorphism (Kamona, 1993; Cairney and Kerr, 1998; Kamona and Friedrich, 2007). Metamorphism could have occurred during the D_2 Monwezian tectonic events between 603 and 512 Ma. The minimum age limit for pre-tectonic Zn–Pb deposits may therefore be regarded as 512 Ma, which represents the maximum cooling age of micas in the Domes Region (Cosi et al., 1992; John et al., 2004).

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 margin of the Congo craton. Many of these are similar to the Zn–(Cu)–Pb deposits in the Central African Copperbelt. On the basis of regional correlations (Batumike et al., 2007; Cailteux et al., 2007; Kamona and Günzel, 2007), these deposits and occurrences are hosted in carbonate units of the Otavi Group that are stratigraphically equivalent to the Nuombe Subgroup (e.g., the Zn–Pb–V Berg Aukas deposit in the Abenab Subgroup) or to the Gombela Subgroup rocks (e.g., the Cu–Pb–Zn Khusib Springs, Pb–Cu–Zn Tsumeb and Cu–Pb Kombat deposits in the Tsumeb Subgroup) in Congo (Table 9).

The age of the Abenab Subgroup, which contains typical Zn–Pb–V Mississippi Valley-type (MVT) deposits such as Berg Aukas and Abenab West hosted in carbonates of the Gauss and Auros Formations, respectively (Kamona and Günzel, 2007 and references therein), is constrained between 746 ± 2 and 635.5 ± 1.2 Ma, which are the respective ages of the Chuos and Ghaub glaciation events in Namibia (Hoffman et al., 1998; Hoffmann et al., 2004). The age of the Tsumeb Subgroup may be bracketed between 635 and 550 Ma, with the latter age being related to collision of the Kalahari and Congo cratons (Stanistreet et al., 1991; Alkmim et al., 2001).

Mineralogically simple Zn–Pb-dominated ores comprising sphalerite, galena, pyrite, minor chalcopyrite, bornite, colusite, reniérite (such as the Berg Aukas deposit) are distinguished from polymetallic ores containing Cu, Pb, Zn, As, and that are considerably enriched in trace elements such as Ag, Cd, Ga, Ge, Mo, and Sb (e.g., Tsumeb deposit). The sulphide assemblages in the latter ores are composed of variable amounts of galena, tennantite, chalcopyrite, sphalerite, chalcocite, enargite, bornite, pyrite, minor germanite, reniérite, briartite, Ge-bearing colusite, and Mo–W sulphides (Lombaard et al., 1986; Hughes, 1987; Melcher, 2003; Melcher et al., 2006). As shown in Table 2, ore from the Khusib Springs deposit has higher Cu–As–Ag–Sb contents than those from Kipushi and Kabwe. The major sulphides in the Khusib Springs deposit are Zn–tennantite, followed by enargite, galena, sphalerite, and pyrite (Melcher et al., 2006). The early stage main sulphide minerals are sphalerite, pyrite, chalcopyrite–bornite, and molybdenite–tungstenite, followed by Zn–tennantite, enargite, galena, pearceite–polybasite and Ge-bearing colusite. Paragenetically, the last formed minerals are Cu-Ag-bearing sphalerite, chalcocite group minerals, Ag-bearing tennantite, tetrahedrite, and Ag-bearing covellite. Compositions of germanite and Ge-bearing colusite from Khusib Springs are shown in Table 3.

Deposition of the ores at Khusib Springs occurred by replacement of carbonates (mainly dolomites) at temperatures reaching 370 °C (Chetty and Frimmel, 2000), preceding or during regional D_2 deformation (Melcher et al., 2006). The sulphur isotope ratios ($\delta^{34}S$ = +20.8 to +27.8‰; mean +23.5‰) suggest that formation of the ore involved highly saline brines carrying sulphur derived from evaporitic sequences.

The pipe-like Tsumeb orebody was the largest Pb–Cu–Zn deposit in the Otavi Mountain Land until its closure in 1996. The mineralization is confined to an ellipsoidal structure on the northern limb of a large syncline, cutting through the uppermost carbonate members of the Tsumeb Subgroup, and reaching a depth of 1400 m below surface. Sulphide ore replaces a feldspathic sandstone representing the infill of a karst-induced breccia pipe, and the host dolostone as manto ores. Due to complex hydrological conditions, sulphide ores have been oxidized to a great depth, producing spectacular secondary mineral specimens of Cu–Zn–Pb carbonates, sulphates, arsenates, vanadates, oxides and silicates. 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., 1999) and volcanic associated deposits such as Rosh Pinah and Skorpion Zinc in the

Table 9
Lithostratigraphy of the Damara Supergroup (Kamona and Günzel, 2007) compared to the Katangan Supergroup (Cailteux et al., 2007), and stratigraphic position of the major deposits.

Supergroup	Group	Subgroup	Formation	Deposit
Damara Supergroup	Mulden		Kombat	
			Tschudi	Tschudi Cu-(Ag)
	Otavi	Tsumeb Subgroup	Huttenberg	Kombat Cu-Pb-(Zn)
			Elandshoeck	Tsumeb Pb-Cu-Zn-(Ge)
			Maieberg	Abenab V ; Khusib Springs Cu-Pb-Zn
			Ghaub (diamictite)	± 635 Ma
		Abenab Subgroup	Auros	Abenab West Pb-Zn-V
			Gauss	Berg Aukas Zn-Pb-V
			Berg Aukas	
			Varianto (diamictite)	± 741 Ma
	Nosib		Askevold	Nosb Cu ; Askevold Cu
			Nabis	
Grootfontein Basement Complex				

Deposit	Formation	Subgroup	Group	Supergroup
< 573 Ma		Biano	Kundelungu	Katangan Supergroup
	Sampwe	Ngule		
Dikulushi Cu-(Ag)	Kiubo			
	Mongwe			
	Lubudi	Gombela		
	Kanianga			
	Lusele			
	Kyandamu (diamictite)			
	Monwezi	Bunkeya	Nguba	
Lombe Zn-Pb	Katete			
Kipushi Zn-Cu-Pb	Kipushi	Nuombe		
Kabwe Zn-Pb ? Kansanshi Cu	Kakontwe			
Kengere Zn-Pb	Kaponda			
± 735 Ma	Mwale (diamictite)			
	Mwashya		Roan	
Kabwe Zn-Pb ?	Dipeta / Kirilabombwe			
stratiform Cu-Co	Mines / Kitwe			
± 880 Ma	RAT / Mindola			
Kibaran & pre-Kibaran basement				

Gariep Belt of Namibia (Frimmel et al., 2004). The Tsumeb deposit occurs in folded and highly fractured carbonate zones and its ca. 530 Ma age of mineralization (Kamona and Günzel, 2007) is syntectonic in relation to the second phase of the Damaran Orogeny that occurred between ca. 570 and 520 Ma (Kröner, 1982; Haack and Martin, 1983; Haack et al., 1983).

The Kombat mine 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 orebodies that terminate at the contact with overlying slates. Massive to semi-massive sulphide ore is best developed in zones of brecciation within dolostone and associated feldspathic sandstone lenses. The ore consists of chalcopyrite, bornite, galena, chalcocite, minor sphalerite, tennantite, betechthinite, arsenopyrite, enargite, reniérite and colusite (Innes and Chaplin, 1986; Kamona and Günzel, 2007). The presence of stratiform 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 fold belt

The Neoproterozoic 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. 4000-m thick pre-Pan-African passive-margin platform siliciclastic and carbonate sequences of the Sansikwa, Haut Shiloango, and Schisto-Calcaire subgroups, and ca. 2000-m thick late- to post-Pan-African molasse sequences of the Mpioka and Inkisi subgroups (Tack et al., 2001). The lowermost Sansikwa Subgroup unconformably overlies a granitic basement. The base of the Haut Shiloango and of the Schisto–Calcaire subgroups are marked by two regionally extensive diamictites named "Lower Mixtite" (ca. 400-m thick) and "Upper Mixtite" (ca. 150-m thick), respectively. The Lower Mixtite represents the glaciogenic Sturtian event, while the Upper Mixtie is of Marinoan age (Poidevin, 2007). The molasse sequences deposited in foreland basins (Tack et al., 2001).

The Bamba-Kilenda Cu–Pb–Zn deposit, 70 km south of Kinshasa, is the most documented in the area; it extends over >3.5 km along a major E–W fault in contact with the Schisto-Calcaire, Mpioka and Insiki subgroups, and shows strong similarities with the Kipushi deposit (Cahen, 1954; Kanda Nkula et al., 2003). Mineral resources amount to ca. 150,000 tons metal (Cu + Pb + Zn). The primary sulphide mineralization consists of impregnations and occasional massive lenses hosted in siliciclastic beds of the Mpioka unit, and veins in limestone beds of the Schisto–Calcaire; it occurs also along the contact limestone–siliciclastic rock. The Cu (as chalcocite) occurs predominantly in the western part of the deposit, while Pb–Zn ores (sphalerite–pyrite–galena) associated with V, Ge, Ag, and low Cu (as chalcopyrite–bornite) are characteristic of the eastern part. Ge is contained in sphalerite and Ag in galena. A paragenetic study of the primary ores indicates that pyrite and sphalerite deposited in the early stages, 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 Kabwe (Taylor, 1954) and Kipushi (Thoreau, 1928; Intiomale and Oosterbosch, 1974; Walraven and Chabu, 1994);
b) Basin dewatering models involving (i) evolved connate fluids that leached metals from the sedimentary pile, including the early rift sediments (Kortman, 1972; Hughes et al., 1984), or (ii) tectonic brines expelled during orogenesis (Duane and Saggerson, 1995; Kamona et al., 1999; Kamona and Friedrich, 2007), or (iii) fluids produced by metamorphic dewatering (Unrug, 1988, 1989);
c) The dissolution of a salt diapir for the Kipushi deposit (De Magnée and François, 1988);
d) Contemporaneous karst formation and mineralization pre-dating orogenesis for Kipushi (Chabu, 1990) and Kabwe (Samama et al., 1988; Sweeney and Binda, 1989);
e) Remobilization of synsedimentary or proto-volcanogenic ores for Kabwe (Sweeney et al., 1990).

The plethora of genetic hypotheses may be attributed to differences in attitudes over the timing of the mineralization in relation to rifting, sedimentation, tectonic uplift, orogenesis and metamorphism. Complications are also created by the variable source rocks proposed for the metals and sulphur, 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 Nguba Group, characterized by shallow water marine carbonates, dominantly dolomitic, associated with organic-rich facies: stromatolitic or oncolitic structures, dark grey to black micritic and oolitic carbonates, finely bedded organic-rich layers with disseminated stratiform pyrite and chalcopyrite. The presence of relics and pseudomorphs after evaporitic minerals, and dissolution breccias indicate an evaporitic environment of deposition. The lithostratigraphic position of the deposits in Zambia is poorly constrained (except for Kabwe), and is subject to debate between Upper Roan and Nguba units. However, the

Table 10
Lithostratigraphy of the West Congolian Group (Tack et al., 2001) compared to the simplified Katangan succession, and stratigraphic position of the Bamba-Kilenda and Kipushi deposits.

Group	Subgroup	
	Insiki	< 566 Ma
West-Congolian	Mpioka Cu-Pb-Zn	
	Schisto-Calcaire	
	Upper Mixtite (diamictite)	
	Haut Shiloango	
	Lower Mixtite (diamictite)	
	Sansikwa	
Lufu Granite basement		917 Ma

Formation		Subgroup	Group	Supergroup
< 573 Ma		Biano	Kundelungu	Katangan
		Ngule		
± 635 Ma	Kyandamu (diamictite)	Gombela		
		Bunkeya	Nguba	
± 735 Ma	Zn-Pb-Cu Mwale (diamictite)	Muombe		
			Roan	
± 880 Ma	Kibaran & pre-Kibaran basement			

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 Cailteux, 1981). Dikulushi is an exception to this rule, being hosted in sandstones and intraformational 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 (D_2) deformation event of the Lufilian orogenesis.

The primary Zn–Pb mineralization consists of sulfides, and is locally associated with significant concentrations of Cu (e.g., at Kipushi in Congo, at Mufukushi and Lukusashi in Zambia). Zinc represents the most important commodity. Sphalerite, Chalcocite, bornite, chalcopyrite (where copper occurs), galena and pyrite form the main mineral association. Minor Cd, Co, Ge, Ag, Re, As, Mo, and Ga occur at Kipushi, while minor V, Ag, Cd, Cu occur at Kabwe, and only minor V at Airfield, Carmanor and Chiwanda in Zambia. By contrast, the Dikulushi deposit in Congo contains mainly Cu besides minor Zn, Pb, Ag, and As, and Kansanshi in Zambia only Cu and Au.

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 Dipeta/Kiriabombwe and Kansuki sedimentary rocks, while hydrothermal events affected the stratiform Cu–Co ores between ~603 and ~512 Ma (Richards et al., 1988a,b; Kampunzu and Cailteux, 1999; Lerouge et al., 2004; Rainaud et al., 2005b). According to John et al. (2004), geochemical data obtained from eclogites, metagabbros and gabbros in central Zambia provide evidence that they formed at an oceanic spreading centre and that they are relics of a subducted Neoproterozoic oceanic crust. The age of the mafic grabbroic bodies in the Lufilian Arc indicates that spreading occurred at ca. 765–735 Ma, whereas subduction is constrained by the timing of eclogite formation at ca. 638–600 Ma in the Zambezi Belt (John et al., 2003). The spreading event and the subduction event are significantly older than the recently obtained ~450 Ma age of the Kipushi Zn–(Cu)–Pb ores.

As suggested by Kamona et al. (1999), a candidate for the younger igneous event that could be related to mineralization at Kipushi is the post-metamorphic hypabyssal syenite intrusions in the Domes area south of Kipushi, for which U–Pb zircon ages of 458 to 427 Ma have been obtained (Cosi et al., 1992). Other Katangan granitic/syenitic igneous rocks (such as the Hook massif) are clustered to the South of the Domes Area, several hundreds km south of the Copperbelt (Fig. 2). These igneous rocks are late- to post-kinematic intrusives with U–Pb zircon ages of ~570–530 Ma (Hanson et al., 1993), and are thus older than the Kipushi deposit and about 100 Ma younger than the Kabwe deposit.

10.2. Ages of Zn–Pb mineralization

The 230 My age difference between Kabwe (680 Ma) and Kipushi (450 Ma) suggests that two major mineralizing events are responsible for the main Pb–Zn mineralization in the Lufilian Arc. The 680 My event may be correlated with ore-forming processes associated with fluid expulsion during the collision phase of the Lufilian Orogeny, whereas the 450 Ma event is clearly post-tectonic. Therefore the two major Pb–Zn deposits of Kabwe and Kipushi probably represent syntectonic and post-tectonic types of mineralization, respectively.

Another ore-forming event is indicated by the 514 ± 1.2 Ma and 502 ± 1.2 Ma Re–Os ages of Cu–Au vein mineralization at Kansanshi (Torrealday et al., 2000) and by a 514 ± 2 Ma hydrothermal event recognized at Musoshi (Richards et al., 1988a,b). The 514 Ma event probably represents syn- to post-metamorphic ore-forming processes as indicated by the 512 Ma cooling ages in micas (Cosi et al., 1992; John et al., 2004) and by the occurrence of two phase (liquid + vapour) CO_2-rich fluid inclusions in quartz veins at Kansanshi (Kamona, unpublished data).

These age constraints suggest that epigenetic hydrothermal mineralization in the Lufilian Arc occurred episodically over a prolonged period during basin evolution in the Central African Copperbelt and is represented by syntectonic (Kabwe Pb–Zn), metamorphic (Kansanshi Cu–Au) and post-tectonic (Kipushi Zn–Cu–Pb) ore types.

10.3. Ore fluid composition and temperature of deposition

Fluid inclusions studies indicate at least two stages of mineralization at the Kipushi Zn–(Cu)–Pb, Kabwe Zn–Pb, and Dikulushi Cu–(Zn–Pb–Ag) deposits. The first stage is characterized by ore fluids with high temperature and salinity, which have comparable values with those observed in veins and tectonic breccia from stratiform Cu–Co deposits in Congo (e.g., Musoshi and Luiswishi; Fig. 20). The high salinity of these fluids may be due to extensive evaporation of seawater, dissolution of Roan Group evaporites or mixing between these end-member water types (Hanor, 1996).

The second stage, marked by lower temperature and salinities, is characterized by values comparable to those of the Berg Aukas and Tsumeb deposits, and falls in the range of Irish-type Zn–Pb deposits (Misi et al., 2005). The decrease in salinity with decreasing temperature shown by these secondary fluid inclusion populations could result from mixing of hot fluids with low-temperature dewatering solutions associated with the thrust tectonics of the Lufilian orogeny (Cailteux and Kampunzu, 1995), and/or mixing with meteoric water for Kabwe (Kamona and Friedrich, 2007), or from a simple cooling with deposition of NaCl (Richards et al., 1988a).

10.4. Source of metals

The homogeneous lead isotope ratios of galena from Kabwe (Kamona et al., 1999) support the presence of upper crustal source rocks with relatively high $^{238}U/^{204}Pb$ (10.31) and $^{232}Th/^{204}Pb$ (43.08) ratios compared to the Kipushi deposit which has lower $^{238}U/^{204}Pb$ (9.84) and $^{232}Th/^{204}Pb$ (36.33) ratios more typical of conformable massive sulphide deposits (Stacey and Kramers, 1975). Walraven and Chabu (1994) and Kamona et al. (1999) interpreted the lower isotopic 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 Schneider et al. (2007), combined with initial $^{87}Sr/^{86}Sr$ and $^{187}Os/^{188}Os$ ratios for Kipushi sulphides indicate upper crustal metal sources.

10.5. Source of sulphur

The ore deposits are associated with rocks showing evaporitic conditions, suggesting a marine origin for the sulphur. The negative and homogeneous sulphur isotope ratios of ore sulphides (−18 to −12‰ $\delta^{34}S$) from Kabwe (Kamona and Friedrich, 2007) are typical of sedimentary sulphides produced through bacterial reduction of seawater sulphate and suggest a sedimentary source for the sulphur. Other Zn–Pb occurrences with similar sulphur isotope ratios (Dechow and Jensen, 1965) to Kabwe include Itawa (Fig. 2) and Millberg (Fig. 15). The sulphur isotope ratios for Kipushi sulphides show a wide range from heavy (+19.2‰ $\delta^{34}S$) to light (−2.6‰ $\delta^{34}S$) values (Dechow and Jensen, 1965), with sulphides from the Kakontwe Limestone being heavier and more homogeneous (+12.8 to +19.2‰ $\delta^{34}S$) compared to those from the shale of the Katete/Série Récurrente Formation (−2.6 to +18.0‰ $\delta^{34}S$). The heavy isotope ratios from the Kakontwe Limestone are close to the average value of +17.5‰ $\delta^{34}S$ for Neoproterozoic seawater sulphate on the Copperbelt (Dechow and Jensen, 1965; Claypool et al., 1980). A seawater sulphate source is therefore suggested for the Kipushi deposit.

10.6. Genetic model

The Pb–Zn deposits in the Lufilian Arc are similar to Mississippi Valley-type (MVT) deposits, which are typically stratabound, epigenetic orebodies that occur in clusters in carbonate formations of mineral districts spread over large areas (Ohle, 1959, 1967; Snyder, 1967; Heyl, 1968). Like carbonate-hosted sedimentary-exhalative (SEDEX) deposits, MVT deposits are characterized by the absence of obviously associated igneous rocks, but the stratabound and often stratiform morphology of the former deposits contrasts with the majority of MVT deposits whose morphology commonly cross-cuts stratigraphy (Hitzman and Large, 1986; Sangster, 1990). SEDEX deposits are also characterized by an active tectonic setting during mineralization and low to moderate temperatures (100 to 260 °C) of ore formation with salinities from 8 to 28 wt.% NaCl equivalent (Roedder, 1984; Andrew, 1986; Hitzman and Large, 1986; Samson and Russell, 1987). In addition, SEDEX deposits comprise multiple or single lenses of laminated to massive sphalerite, galena, Ag-bearing sulphosalts and pyrite (McGoldrick et al., 1999).

In contrast, the mode of occurrence of MVT deposits is characterized by epigenetic open-space filling with associated mineralization in breccias, along bedding planes and fractures. The ore fluids of MVT deposits typically have low formation temperatures (75 to 200 °C), uniform salinity (>10 wt.% NaCl equivalent), density and composition (Roedder, 1967, 1984; Leach and Sangster, 1993). Higher homogenization temperatures (150 to 280 °C) have, however, been reported from MVT brines in the Reelfoot Rift Complex of south-central USA (Leach et al., 1997). Therefore there are considerable similarities and overlaps between ore fluids of both SEDEX and MVT deposits in terms of formation temperatures, salinities and compositions due to the fact that both SEDEX and MVT deposits form from formation waters derived from sedimentary or metasedimentary basins under high heat flows.

The hypothesis that low-temperature pre-kinematic mineralizing fluids of basinal origin trapped in paleokarsts (Chabu, 1990) may have been responsible for formation of Pb–Zn deposits in the Lufilian Arc is unlikely because of the high fluid inclusion temperatures and salinities recorded from these ores. Intiomale (1982) indicated that the paleokarsts and solution breccias at Kipushi developed during the emplacement of ascending hydrothermal fluids. Hydrothermal karst phenomena are a widespread feature in MVT Zn–Pb ore deposits as indicated by several studies of stratabound Zn–Pb deposits (Sass-Gustkiewicz et al., 1982; Dzulynski and Sass-Gustkiewicz, 1985).

The moderate to high temperatures and salinities recorded in the fluid inclusions in Pb–Zn deposits in the Lufilian Arc indicate that the ore-bearing fluids originated as hydrothermal fluids within the sedimentary basin. The Pb- and S-isotopic compositions also suggest that the source of the mineralizing brines was within the Roan sediments. Metal-rich brines are known to form as a result of diagenetic destruction or alteration of metal-bearing solid phases in the presence of aqueous fluids of high salinity and low H_2S (Hanor, 1996). Chloride complexing results in the preferential partitioning of metals in the aqueous solution. Sulphide deposition occurred within favourable structures such as faults and breccias from chloride complexed metals in the presence of reduced sulphur (H_2S).

A high heat flow within the sedimentary basin could be produced by normal geothermal gradients during basin evolution (Garven et al., 1993). In addition, the magmatic activity associated with the formation of the gabbros and mafic lavas between 765 and 735 Ma, could have contributed to the high heat flow in the sedimentary basin.

Geological evidence of synchronous dewatering and decollement developments in foreland basins during orogenesis has been documented elsewhere (e.g., Jansma and Speed, 1993). Therefore, it is suggested that early ore-forming brines responsible for syntectonic deposits such as Kabwe probably originated from dewatering triggered by sediment loading in the basin or induced by tectonic compression and related metamorphism during the Lufilian Orogeny (e.g., Cailteux and Kampunzu, 1995; Kamona et al., 1999). The occurrence of high pressure rocks (whiteschists) containing zincian-spinels in the Copperbelt and in central Zambia (John et al., 2003, 2004) provide evidence for dewatering of Katangan sediments during subduction from ca. 750 to 600 Ma to produce the Zn–Pb fluids responsible for syntectonic deposits. Post-tectonic deposits such as Kipushi could be related to a later extension event associated with the emplacement of syenite intrusions between 458 and 428 Ma.

Tectonic expulsion of ore fluids is in agreement with current geotectonic models (Kampunzu et al., 1991, 1993; Sebagenzi, 1993; Kampunzu and Cailteux, 1999) based on metamorphic petrology, structural and gravity data showing that young oceanic crust on the southern margin of the Congo craton was subducted beneath the Kalahari craton during the early stages of the Lufilian Orogeny. Several studies have shown that mineralizing fluids in MVT deposits were tectonically expelled during orogenic events (Cathless and Smith, 1983; Leach et al., 1984; Hearn and Sutter, 1985; Oliver, 1986; Duane and de Wit, 1988; Duane and Kruger, 1991). Such internally sourced subduction-zone fluids are expelled from sediments and/or oceanic crust by porosity-reduction processes, biogenic or thermogenic decomposition of organic matter, diagenetic/metamorphic dehydration and/or breakdown of hydrous minerals (Kastner et al., 1990, 1991; Peacock, 1990; Bekins and Dreiss, 1992). Fluid transport could have occurred via a complex system of faults which is generally common in orogenic settings (e.g., Kastner et al., 1990; Le Pichon et al., 1990).

The location of the Katangan Zn–Pb–(Cu) deposits on the northern foreland supports migration of fluids from the subduction zones in the south to the foreland in the north. Recent field observations indicate that thrust sheets carrying Katangan sediments occur in the inner zone of the Copperbelt, at least in the western part of Zambia south of the Domes Area. According to Kampunzu et al. (2005), these sediments derived from Palaeoproterozoic rocks and deposited in the accretion prism on the northern margin of the Kalahari craton (which was the overlying plate during the Katangan subduction), and finally were thrusted and transported towards the northern foreland. The Katangan rocks in western Zambia may represent the roots for the Katangan nappes in Congo. The Kansanshi Cu deposit that occurs in this area is marked by Au-rich compositions, typical of the copper deposits hosted in the Mines Subgroup in Congo. This suggests, for this deposit, that the Congolese facies of the Katangan succession represents the leached sediments.

The abundance of Cu and minor metals depends on ore–fluid characteristics. According to Huston et al. (2006) transport of Cu and Au (e.g., in the Kipushi and Kansanshi deposits) requires that the ore fluids must have: (1) temperature <250 °C, H_2S poor, and not in equilibrium with pyrite; or (2) temperature >250 °C, H_2S-rich, and in equilibrium with pyrite. Fluid transport and ore deposition could have occurred through any of these three models that have been developed for MVT systems: (1) transportation of metals and reduced sulphur together in a basinal brine (Sverjensky, 1984); (2) transportation of metals and sulphates together in a basinal brine (Anderson, 1975; Beales, 1975); (3) mixing of metals in a basinal brine and sulphur derived from sources at the deposition site or from a second fluid (Beales and Jackson, 1966). Ore deposition could have taken place as a result of pH change, addition of H_2S, dilution (fluid mixing) or cooling (Barnes, 1983).

The sulphur isotopes at Kipushi are typically heavy (> +12‰ and < +20‰) and similar to the values recorded in the Katangan sulphates (Cailteux et al., 2005b). Kipushi is characterized by the presence of gypsum, anhydrite and organic matter which occur in all the Zn–Pb deposits in the Copperbelt. These minerals suggest that probably the H_2S in the Kipushi deposit was derived locally through abiological reactions involving Katangan sedimentary sulphate, organic matter and H_2S. A similar model was proposed for Pine Point in Arctic Canada (Macqueen and Powell, 1983; Powell and Macqueen, 1984).

Generally MVT brines are rich in Ba and F. The fluids at Kipushi contained both elements as indicated by neoformed F-rich phlogopites in the ores, barium–potassium feldspars, Ba-rich muscovites and barite. In addition, Ba–Fe veins (barite–hematite) of centimetre to metre thickness are known in the Copperbelt (e.g., in the Kimbwe and Kambove-Kabolela areas, Fig. 3), associated with faults developed during the second (D_2) deformation event of the Lufilian orogenesis, and cutting across the Kundelungu, Nguba and Roan (Mwashya, Dipeta) successions (Mbuyi, 1984; Intiomale and Mbuyi, 1997). Although these veins remain poorly documented, the current data suggest that they are also part of the MVT mineralizing event that produced Zn–Pb–Cu deposits in the Central African Copperbelt.

11. Conclusions

The Lufilian Arc of the Central African Copperbelt is a complex metallogenic province containing stratiform sediment-hosted Cu–(Co)–(U) deposits largely of syndiagenetic to diagenetic origin as well as stratabound Zn–Pb–(Cu) carbonate-hosted deposits of epigenetic origin and post-tectonic, hydrothermal vein-type Cu–(Au)–(Ag). 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. 880 to 512 Ma.

The Zn–Pb–(Cu) deposits of the Lufilian Arc formed from basinal brines during two main mineralizing events that characterize syntectonic deposits (e.g., Kabwe) and post-tectonic deposits (e.g., Kipushi). These deposits exhibit many of the typical characteristics of Mississipi Valley-type ore-forming systems, including their classical stratabound, epigenetic nature and occurrence in clusters within platform marine carbonates overlying continental crust. A sialic crustal origin of the metals from basinal sediments and basement rocks is supported by lead and strontium isotope data, whereas the sulphur isotope compositions are compatible with a sedimentary origin of sulphur from seawater via evaporites and/or diagenetic sulphides. 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 karsts as a result of cooling, fluid mixing, pH change or addition of H_2S.

More data is required to better constrain the timing of the mineralization, but current data suggests that the carbonate-hosted Zn–Pb–(Cu) deposits of the Lufilian Arc formed over a time period spanning 230 Ma and include both syntectonic and post-tectonic types in relation to the Lufilian Orogeny. The polymetallic nature, fluid inclusion characteristics, mode of occurrence, structural control and stratigraphic positions of the deposits are comparable to deposits found in the deformed Neoproterozoic West-Congolian (e.g., Bamba-Kilenda) and Damaran belts (e.g., Tsumeb, Kombat and Berg Aukas) as well as some Pb–Zn deposits in Brazil (e.g., Morro Agudo, Vazante, Nova Redenção).

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