

The origin of the Central African Copperbelt: in a nutshell

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The Central African Copperbelt, the largest resource of Cu and Co in the world, straddles the international boundary between Zambia and the Democratic Republic of Congo (DRC). A major sedimentological facies change coincides with or is very close to this international border. For decades these two countries were controlled by two different colonial powers, Britain and Belgium respectively. The political, administrative, and language boundaries between these colonial powers also led to very powerful scientific and technological boundaries.

The sedimentological facies change coinciding with the international border led to scientists from both colonial powers often observing and studying only their respective sides of the border. The end of colonialism eventually resulted in nationalization of the mines in both Zambia and the DRC, with minimal scientific work being conducted for nearly two decades. When these countries again became accessible to multinational mining companies in the late 1990s to early 2000s, many workers had for the first time the opportunity to work across the international border to observe and study the 'complete' Copperbelt.

The more siliciclastic sediments proximal to the underlying basement 'granites' often dominate the stratobound ore horizon on the Zambian side. The presence of K-feldspar, biotite/phlogopite, muscovite and an associated 'enrichment' in potassium often led workers to believe that these may represent signs of hydrothermal K-metasomatism related to later metal-bearing epigenetic fluids. These are, however, all of a sedimentary origin. The basement provenance from which these sediments originated is of an alkali granite/granitoid composition, possible very similar to those associated with Ernest Henry/Olympic Dam-type Fe-Cu(Co)-U±Au deposits. These may have been the original source of the Cu-Co±U, now concentrated within the Copperbelt 'ore shale'. Signs of evaporitic precursors are sporadically present on the Zambian side, with dolomite the most common.

However, as the more basement-distal sabkha-type evaporitic chemical sediments start to dominate on the DRC side of the border, the complete picture of a 'Kupferschiefer-type' deposit emerges. Here sabkha conditions prevailed across a wide carbonate inner ramp, with coastal sabkhas and alternating shallow marine incursions. Evaporitic dolostones formed during dry cycles and siltstones during wet ones. Anoxic conditions prevailed within the sabkha lagoons – often cut off from fresh sea water influx during dry cycles. This led to the preservation of organic carbon and the formation of syngenetic to early diagenetic pyrite. Carbonatization and dolomitization of evaporites results in the creation of increased secondary porosity (up to a maximum of 22%). The presence of magnesite indicates that late-stage subsurface dolomitization occurred at greater depth and higher temperatures.

Thermochemical sulphate reduction (TSR) and/or bacterial sulphate reduction (BSR) and associated dissolution of evaporitic sulphates subsequently occurred ($2\text{CH}_2\text{O} + \text{SO}_4^{2-} = 2\text{HCO}_3^- + \text{H}_2\text{S}$). Organic carbon is needed for BSR, with CO_2 and H_2S being produced. This CO_2 can also cause carbonate dissolution, which can further increase the porosity. The pores are thus filled with reducing H_2S - and CO_2 -rich fluids. 'Secondary' diagenetic carbonates and Fe sulphides can be formed.

Introduction of an oxidizing Cu-Co metal-bearing brine must have taken place before secondary porosity and permeability were destroyed by subsequent metamorphic events. This is effectively a mixing of two fluids – (1) a reducing H_2S -rich pore fluid residing within the host rocks and (2) an oxidizing Cu-Co metal-bearing fluid originating from

basinal brines due to dewatering of the underlying siliciclastic filled basin. Hydrothermal phases then fill the secondary porosity, namely (i) Cu- and Co-sulphides, (ii) quartz, and (iii) dolomite. This diagenetic mineralization event was later overprinted by greenschist facies regional metamorphism, which resulted in some localized remobilization of precursor phases.

Introduction

The Central African Copperbelt, the largest resource of Cu and Co in the world, straddles the international boundary between Zambia and the Democratic Republic of Congo (DRC) (Figure 1). A major sedimentological facies change coincides with or is very close to this international border. For decades these two countries were controlled by two different colonial powers, Britain and Belgium respectively. The political, administrative, and language boundaries between these colonial powers also lead to very powerful scientific and technological boundaries.

The sedimentological facies change coinciding with the international border led to scientists from both colonial powers often observing and studying only their respective sides of the border. The end of colonialism eventually resulted in nationalization of the mines in both Zambia and the DRC, with minimal scientific work being conducted for nearly two decades. When these countries again became accessible to multinational mining companies in the late 1990s to early 2000s, for the first time many workers had the opportunity to work across the international border to observe and study the ‘complete’ Copperbelt.

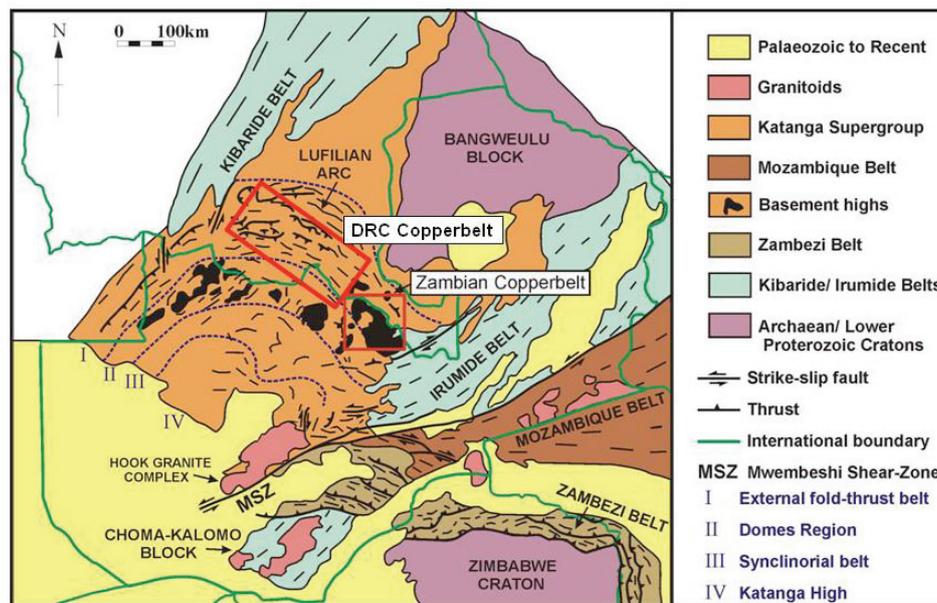


Figure 1. Regional geological setting of the Central African Copperbelt, divided by international boundaries into a basement-proximal Zambian Copperbelt and a basement-distal DRC Copperbelt

Petrological results

An extensive study involving six Cu-Co deposits on the Zambian side of the Central African Copperbelt and four in the DRC was conducted. The orebodies stretched across the Central African Copperbelt from Nkana in the south-east to Kamoto in the north-west (Figure 2). The study included:

- Detailed core logging and associated hand specimen descriptions
- X-ray diffraction (XRD) analyses
- Petrography (reflected and transmitted light)
- Cathodoluminescence microscopy
- Scanning electron microscopy (SEM) and associated energy dispersive spectroscopy (EDS) analyses
- Geochemistry
 - Whole rock multi-element
 - Stable isotope signatures
 - Fluid inclusion microthermometry.

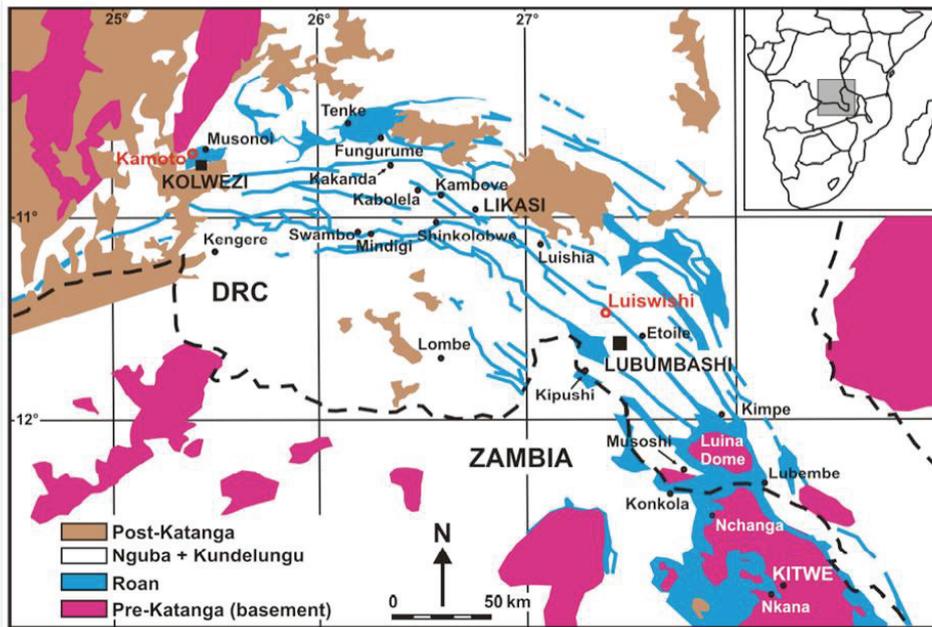


Figure 2. A more localized geological map showing the distribution of the major mines and orebodies throughout the Central African Copperbelt, from Nkana in the south-east to Kamoto in the north-west (after Debruyne et al., 2013)

Changing lithologies and associated mineralogy

The Lower Roan Formation evolves from conglomerates to arkosic arenites and dolomite-rich siltstone-mudstone ‘shales’ in the south-east to carbonate-rich (dolomite ± magnesite) evaporitic mudstones-packstones and carbonaceous black shales in the north-west. A major sedimentary facies change occurs in the Roan Formation along the Zambian-DRC border in the Konkola region, from more siliciclastic to more evaporitic carbonate-rich sediments (Figure 2).

The original sulphide ores, before tectonic-metamorphic effects and supergene overprinting, are in general stratabound and very well layered and laminated, suggesting a very strong lithological and sedimentological control.

The siliciclastic sediments characterizing the Lower Roan Formation on the Zambian side originate directly from the underlying basement granitoids (Figure 3). Although these siliciclastic sediments are characterized by ample quantities of K-bearing minerals, such as K-feldspar, biotite/phlogopite, and muscovite, there is no evidence that these are related to the sulphide mineralisation (Figure 4). Petrographic and geochemical evidence, however, point to a detrital sedimentary origin, with the basement granitoids as the source. These granitoids appears to be at least partly characterized by alkali granites.

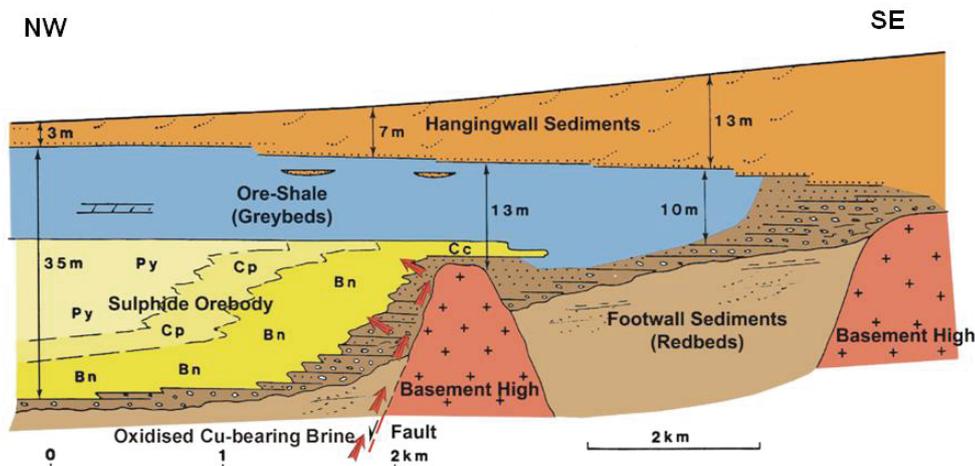


Figure 3. Block model of the basement-proximal Zambian Copperbelt and the footwall oxidized ‘red bed’ sediments lapping onto granitoid basement. These granitoids are in some places known to contain alkali-granitoid-related Fe-oxide-copper-gold (IOCG) deposits, which were a possible primary source of the Cu, Co, and U

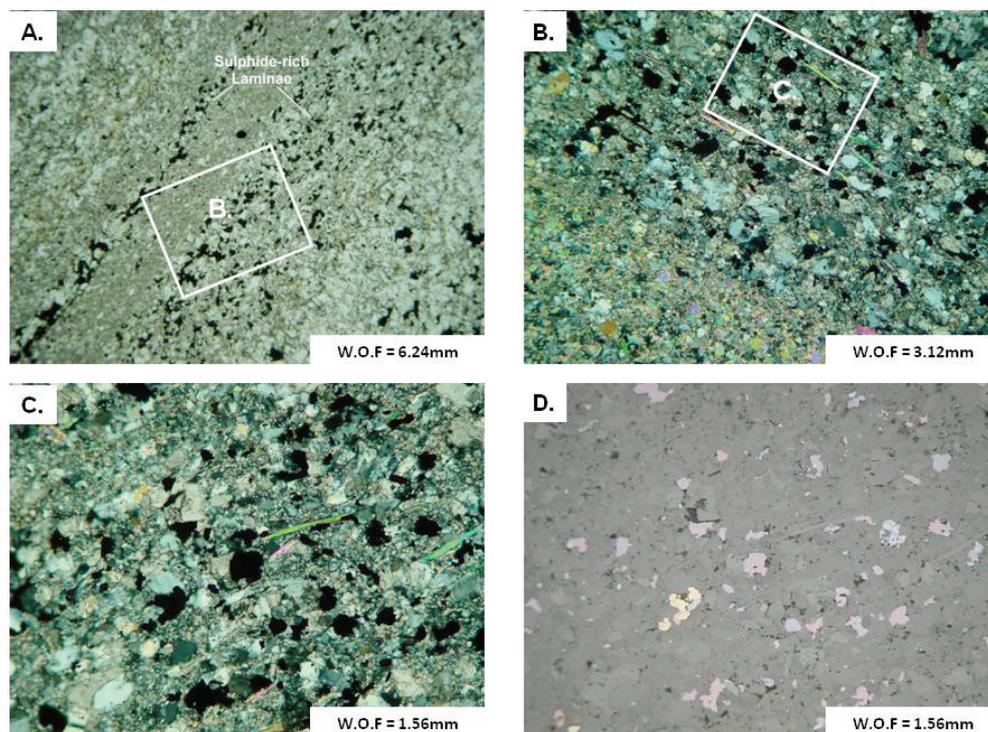
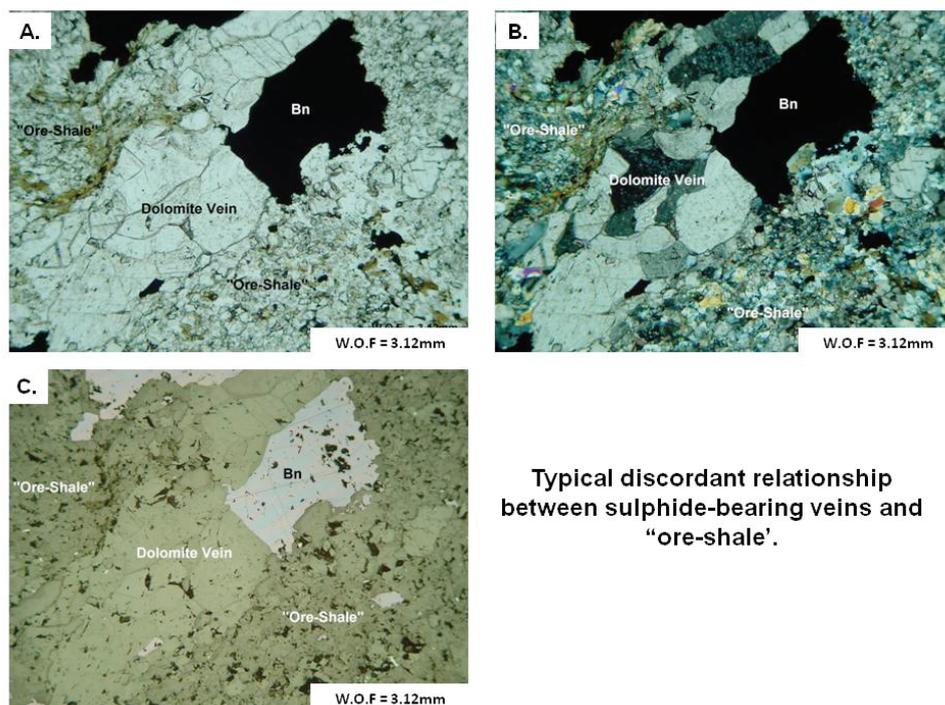


Figure 4. Photomicrograph mosaic of a typical layered to finely laminated 'ore shale' in the Zambian Copperbelt, dominated by silicates, such as quartz, K-feldspar, biotite/phlogopite, and muscovite/sericite. Dolomite is the main interstitial carbonate and Cu-Co sulphides, dominated by primary bornite and chalcopyrite, concentrate along specific layers and laminae. W.O.F. = width of field

The concordant-discordant veins transecting the 'ore-shale' are clearly 'heal' fractures, which resulted from the Lufilian orogeny tectonic deformation and metamorphism events overprinting the original sediments (Figure 5). These 'heal' fractures are characterised by precisely the same minerals, with similar mineral chemistry as those within the surrounding sediments, clearly indicating that the minerals within the veins originated from the surrounding sediments. The Lufilian orogeny thus resulted in localised remobilization and redistribution of most of the phases, including the Cu-Co sulphides.



Typical discordant relationship between sulphide-bearing veins and "ore-shale".

Figure 5. Photomicrograph mosaic of a typical discordant sulphide-bearing veins transecting the layered to finely laminated 'ore shale' in the Zambian Copperbelt. Note the coarse bornite (Bn) and sparry dolomite characterizing the vein. W.O.F. = width of field

Cathodoluminescence microscopy, however, indicates that multiple phases of carbonate (dolomite and magnesite) are present within the mineralized 'Ore Shale' and associated concordant-discordant veins systems (Figure 6). This suggests that conditions did change from the main mineralization diagenetic event to the later orogenic remobilization of these phases. These concordant-discordant mineralized veins are largely restricted to the 'Ore Shale' or the immediately surrounding lithologies, which indicates restricted remobilization.

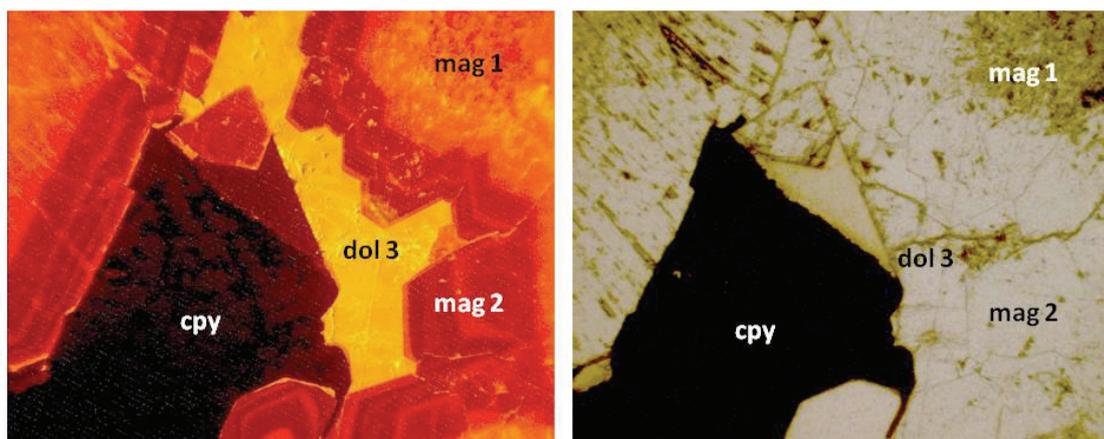


Figure 6. Cathodoluminescence (left) and transmitted light (right) photomicrographs of discordant sulphide-bearing veins transecting the layered to finely laminated 'ore shale' in the DRC Copperbelt. Note the various generations of coarse sparry magnesite (mag) and dolomite (dol) carbonate filling the vein together with chalcopyrite (cpy). No scale

The evaporitic mudstones/packstones, which often have been recrystallized to a marble-like appearance, characterize the Lower Roan Formation in the DRC (Figure 7). Here, in contrast to the more siliciclastic detrital sediments characterizing the Zambian side of the Copperbelt, there is a clear link between the Cu-Co sulphide mineralization and the evaporitic origin of the sediments.

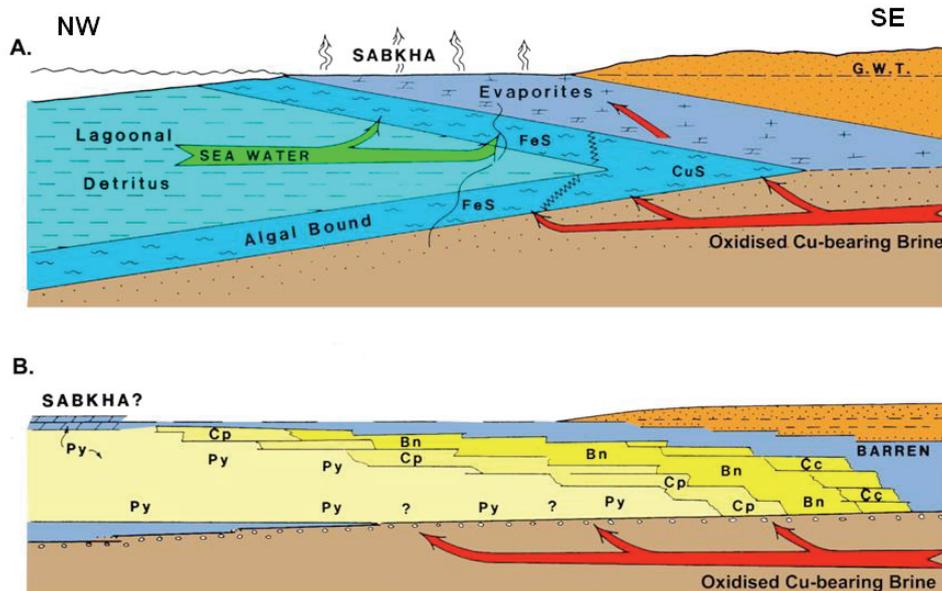
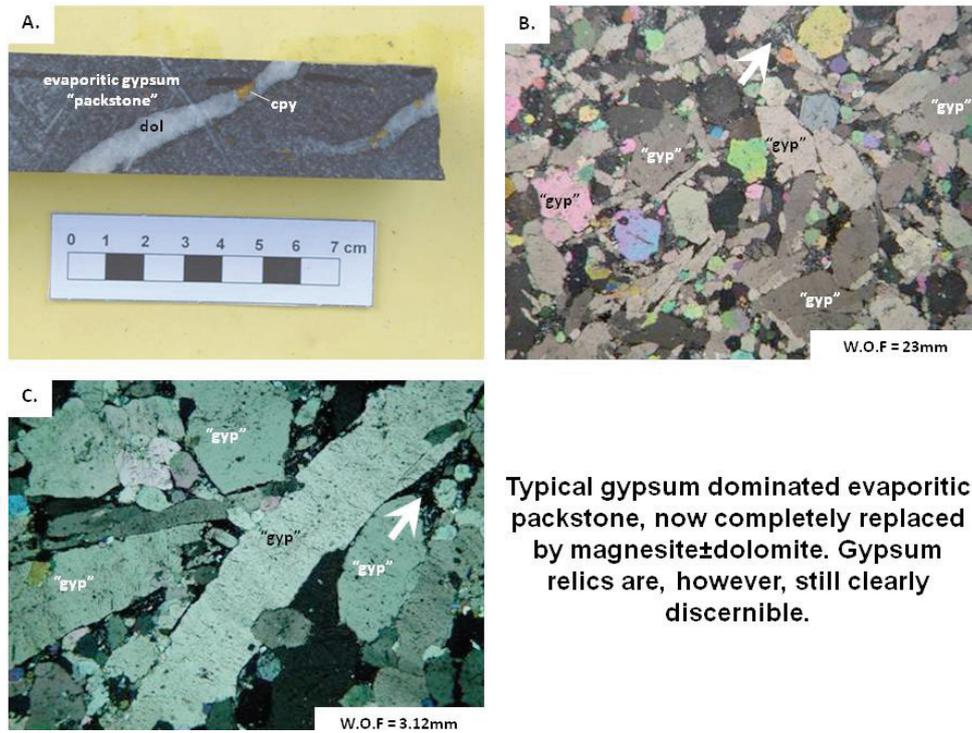


Figure 7. Block model of the basement distal DRC Copperbelt characterized by an evaporitic sabkha environment. It is also the ideal setting for diagenetic dolomitization and the creation of associated secondary porosity, the latter forming the pathways and deposition sites for the Cu and Co brought in by the basinal oxidizing brines

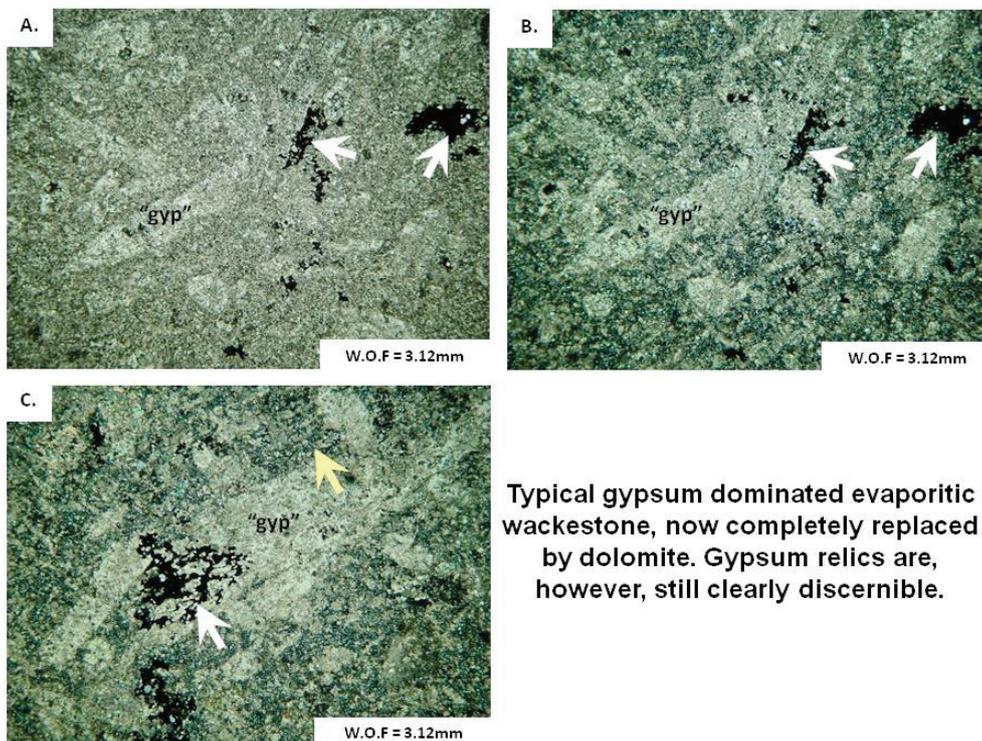
In the siliciclastic detrital sediments the concentration of sulphides along specific layers and laminae clearly indicates a very strong sedimentological control, although the origin of this control is in most cases not clear. Well defined relics of evaporites have been sporadically detected in these siliciclastic detrital sediments, but are generally rare. The abundance of interstitial dolomite within these siliciclastic sediments is, however, suspicious.

The link between the Cu-Co sulphide mineralization and the evaporitic sediments on the DRC side of the Copperbelt is, however, undeniable. Here, ample evidence of Cu-Co sulphides directly replacing evaporite gypsum relics exists (Figures 8 and 9). The evaporites vary from evaporitic gypsum 'packstone' to 'wackestone' beds/layers a couple of centimeters thick to nodular gypsum laminae (several millimeters in width) occurring within black carbonaceous shales and impure dolomitic mudstones.



Typical gypsum dominated evaporitic packstone, now completely replaced by magnesite±dolomite. Gypsum relics are, however, still clearly discernible.

Figure 8. Carbonated evaporite gypsum 'packstone'/'grainstone' transected by discordant dolomite-chalcopyrite (dol-cpy) veins (A). The gypsum relics ('gyp') have been pseudomorphically replaced by magnesite. A microcrystalline quartz and fine fibrous clinoclone matrix (white arrow) occurs interstitial to the gypsum relics (B and C). The disseminated chalcopyrite occurs mainly interstitial to the gypsum relics. W.O.F. = width of field



Typical gypsum dominated evaporitic wackestone, now completely replaced by dolomite. Gypsum relics are, however, still clearly discernible.

Figure 9. Photomicrograph mosaic of a carbonated (dolomite) evaporite gypsum 'packstone' to 'wackestone'. The rock predominantly consists of coarse randomly orientated euhedral gypsum relics ('gyp'), exhibiting prismatic, hexagonal and 'lozenge-' or 'cigar-shaped' outlines (A to C). Irregular chalcopyrite bodies (white arrows) occur interstitial to (A and B) and occasionally intensely intergrown (C) with the gypsum relics. Fine microcrystalline quartz and associated fine clinoclone form the interstitial matrix to the carbonated gypsum relic (yellow arrow). W.O.F. = width of field

There is thus a clear transition from a siliciclastic-dominated detrital depositional environment, proximal to the basement granitoid source in the south-east, to a evaporate-dominated sabkha depositional environment in the north-west. The general lack of primary calcite as well as sediments dominated by an Mg-rich assemblage of dolomite, magnesite, Mg-rich clinocllore and talc, clearly indicates a primary sedimentary environment dominated by the formation of extremely Mg-rich marine brines pumping through the recently deposited shallow marine-lagoonal sediments (Figure 10).

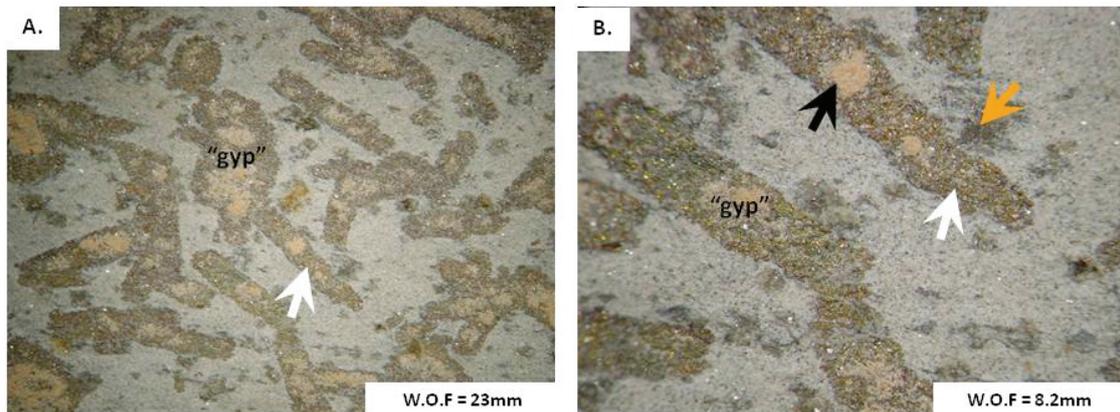


Figure 10. Stereo photomicrographs of an evaporitic bedding plane characterized by abundant randomly orientated evaporite relics ('gyp'), probably after gypsum, completely replaced by chalcopyrite (white arrow) and pink-coloured authigenic monazite crystals and crystal aggregates (black arrow) Minor amounts of carrollite and/or cobaltian pyrite (orange arrow) are also discernible

Geochemical evidence

Oxygen and carbon stable isotopes

The carbonatization of evaporites during diagenesis is quite well known, with dolomite and/or magnesite replacing the original anhydrite/gypsum. The presence of substantial, but not obvious, evaporitic dolomite in the detrital siliciclastic facies of the Zambian Copperbelt indicates that some evaporitic input may have been present. This could represent either original evaporites or evaporitic material remobilized by wave, current, and wind action. For example the Mufulira deposit in Zambia has been described as an orebody hosted by eolian sands.

Due to the lack of sufficient petrological evidence of evaporites on the Zambian side of the Copperbelt, stable isotope O and C analyses were conducted on the interstitial and transecting vein-hosted carbonates (dolomite). The dolomite from the 'Ore Shale' has a unique $\delta^{13}\text{C}$ (PDB) and $\delta^{18}\text{O}$ (SMOW) isotopic signature compared to the Footwall and Hanging-wall dolomites (Figure 11).

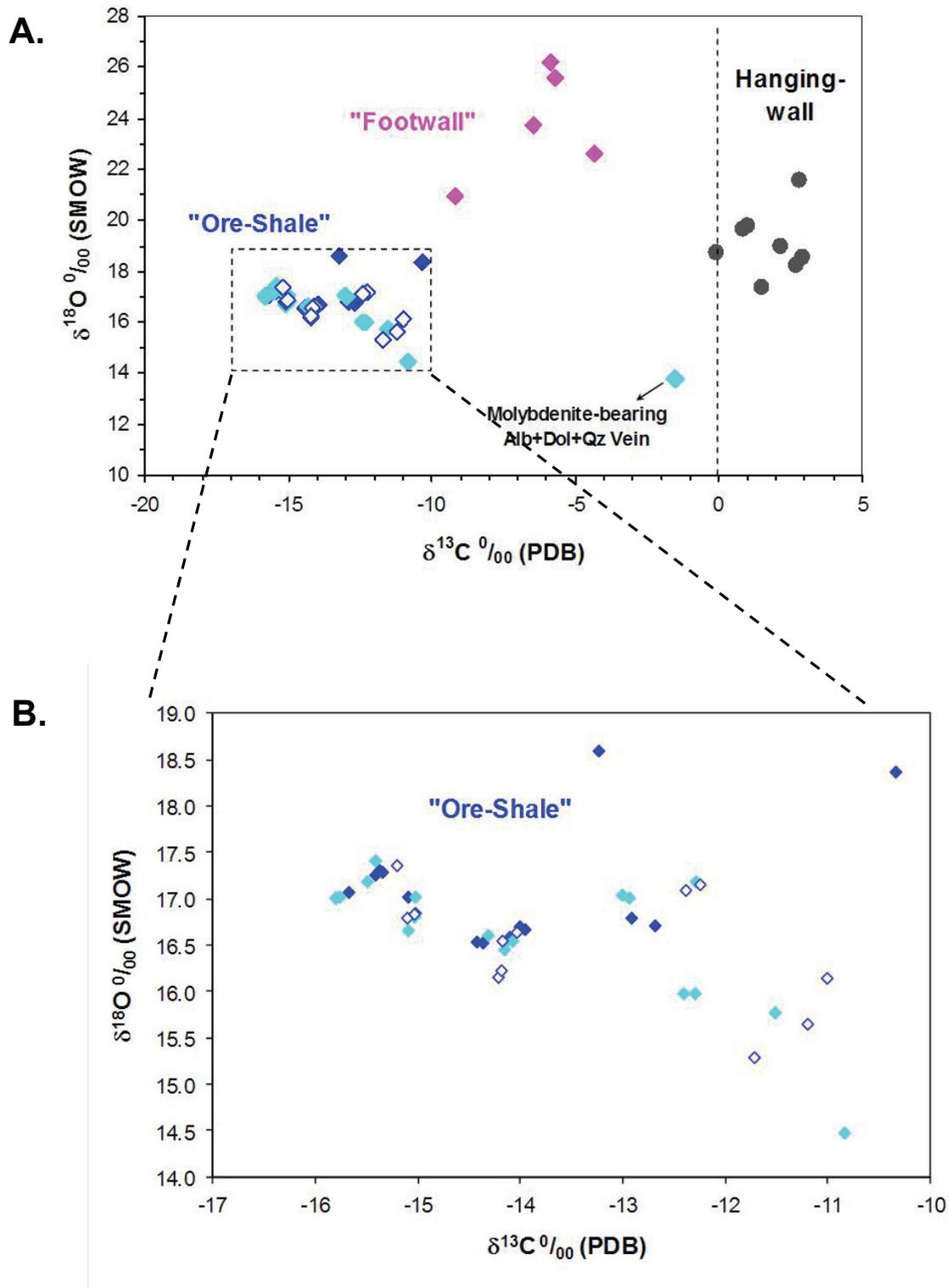


Figure 11. $\delta^{13}\text{C}$ versus $\delta^{18}\text{O}$ plot for dolomitic carbonates from the Zambian Copperbelt. The samples have been classified according to their stratigraphic position. The Hanging-wall samples (black circles) give a marine signature, while the 'Ore Shale' samples (blue diamonds) are characterized by quite low $\delta^{13}\text{C}$ values. The Footwall samples exhibit a nearly intermediate $\delta^{13}\text{C}$ signature between the Hanging-wall and 'Ore Shale' (A). The mineralized host rocks (closed dark blue diamonds), diffused veins (open dark blue diamonds), and concordant-disconcordant veins (closed light blue diamonds) exhibit very similar $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ signatures (B)

The Hanging-wall carbonates give a typical marine $\delta^{13}\text{C}$ (PDB) isotopic signature (0 to 5 $\delta^{13}\text{C}$ ‰), while the 'Ore Shale' is characterized by quite negative $\delta^{13}\text{C}$ (PDB) isotopic values (-10 to -16 $\delta^{13}\text{C}$ ‰) (Figure 11). These negative $\delta^{13}\text{C}$ (PDB) values are most probably the result of the involvement of (i) organic carbon degradation (decarboxylation), (ii) bacterial sulphate reduction, (iii) methane oxidation, and/or (iv) the early stages of methanogenesis (CO_2 reduction) in organic carbon-rich sediments as a source of pore water total dissolved carbon and thus $\delta^{13}\text{C}$ variations (Anderson and Arthur, 1983). There is relatively little carbon isotope fractionation during dolomite precipitation (<2.0 to 3.0 ‰) at low temperatures (<80°C) of diagenesis. The $\delta^{13}\text{C}$ (PDB) values of the dolomites thus closely reflect the $\delta^{13}\text{C}$ (PDB) values of the total dissolved carbon (TDC) in the pore waters (Anderson and Arthur, 1983).

The ingredients for organic carbon degradation, bacterial sulphate reduction, and methanogenesis are thus all present within the 'Ore Shale', and even in the more siliciclastic Zambian facies.

The 'Ore Shale' also has a distinctly lower $\delta^{18}\text{O}$ (SMOW) signature than both the Hanging-wall and Footwall carbonates, possibly indicating higher temperatures of formation and/or a meteoric water input/origin (Figure 11). The Footwall carbonates reflect an intermediate $\delta^{13}\text{C}$ (PDB) isotopic signature, which indicates that the carbon in the carbonates originated at least in part from the same sources as that within the 'Ore Shale' (Figure 11). Higher $\delta^{18}\text{O}$ (SMOW) signatures, similar to the Hanging-wall carbonates, possibly reflect much lower temperatures of formation and/or a marine water oxygen reservoir.

The 'heal' fracture origin of the transecting veins in the 'Ore Shale' is confirmed by the O and C stable isotope geochemistry. Dolomite from the mineralized host rocks, diffused vein selvages, and concordant-discordant veins largely exhibits similar $\delta^{13}\text{C}$ (PDB) and $\delta^{18}\text{O}$ (SMOW) isotopic signatures. However, in some cases the host rocks appear to exhibit relatively higher $\delta^{18}\text{O}$ (SMOW) values than the veins (Figure 11). This suggests slightly higher temperatures of formation and/or a meteoric input in the veins. The higher $\delta^{13}\text{C}$ (PDB) values exhibited by some of the diffused vein selvages and concordant-discordant veins may be related to specific conditions on an orebody scale (Figure 11). The Mufulira deposit is an example of this. At Mufulira, organic carbon degradation (decarboxylation) and methanogenesis (CO_2 reduction) possibly contributed only insignificant amounts to the total dissolved carbon (TDC) of the pore water, as organic material at Mufulira is relatively scarce. Due to the abundance of sulphate at Mufulira, bacterial sulphate reduction may have played a more important role, and this may be reflected in the higher $\delta^{13}\text{C}$ (PDB) values of the Mufulira carbonates.

According to Muchez *et al.* (2008) the depleted $\delta^{13}\text{C}$ (PDB) values are consistent with depletion due to oxidation of organic matter during bacterial sulphate reduction (BSR). More depleted $\delta^{13}\text{C}$ (PDB) values (up to -25 ‰) detected in some coarse discordant-concordant dolomite veins by El Desouky *et al.* (2009) at Kamoto and Luiswishi indicate possible oxidation of organic matter during thermochemical sulphate reduction (TSR) (Machel *et al.*, 1995). The discordant and concordant veins, however, mostly exhibit similar depleted $\delta^{13}\text{C}$ (PDB) values as the host rock; this indicates that these discordant-concordant coarser dolomite veins represent recrystallization of the earlier dolomites (metamorphic overprint). Lower $\delta^{18}\text{O}$ (SMOW) values in some cases, however, indicate that recrystallization took place at higher temperatures.

Sulphur stable isotopes

The evaporitic origin of the 'Ore Shale' in the more siliciclastic Zambian part of the Copperbelt is confirmed by the $\delta^{34}\text{S}$ ‰ (CDT) signature of the sulphides. The $\delta^{34}\text{S}$ ‰ values of the Cu-Co sulphides, including Co-bearing pyrite, varies between 4 and 16 (Figure 12). This is quite different to the early diagenetic pyrite with quite negative $\delta^{34}\text{S}$ ‰ (CDT) values varying between -8 and -16 (McGowan *et al.*, 2006 and Roberts *et al.*, 2005). The latter values are typical of sulphides associated with sedimentary rocks. The positive $\delta^{34}\text{S}$ ‰ (CDT) values of the Cu-Co sulphides, however, reflect a strong marine evaporite sulphate $\delta^{34}\text{S}$ ‰ (CDT) signature (Figure 13) (Holser and Kaplan, 1966). There is thus strong evidence that the sulphur component of the Cu-Co sulphides originated from evaporitic marine sulphates. Petrographic and O and C stable isotope data indicates that these evaporitic marine sulphates were dominated by gypsum and that organic carbon degradation (decarboxylation), bacterial sulphate reduction, and methane oxidation played a role in preparing the diagenetic pore fluids for the metal-bearing brine.

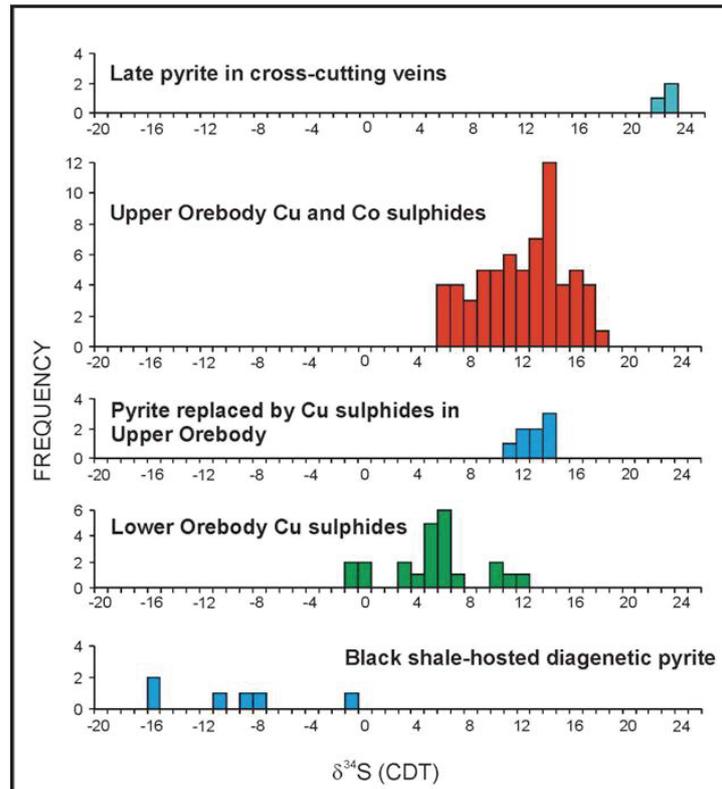


Figure 12. $\delta^{34}\text{S}$ (CDT) frequency plot for sulphides from the Nchanga Cu-Co deposit in Zambia (After McGowan et al., 2006 and Roberts et al., 2005). Note the bulk of the $\delta^{34}\text{S}$ (CDT) values for the Cu and Co sulphides plot between 6 and 18 ‰. CDT = Canyon Diablo Troilite Reference Material

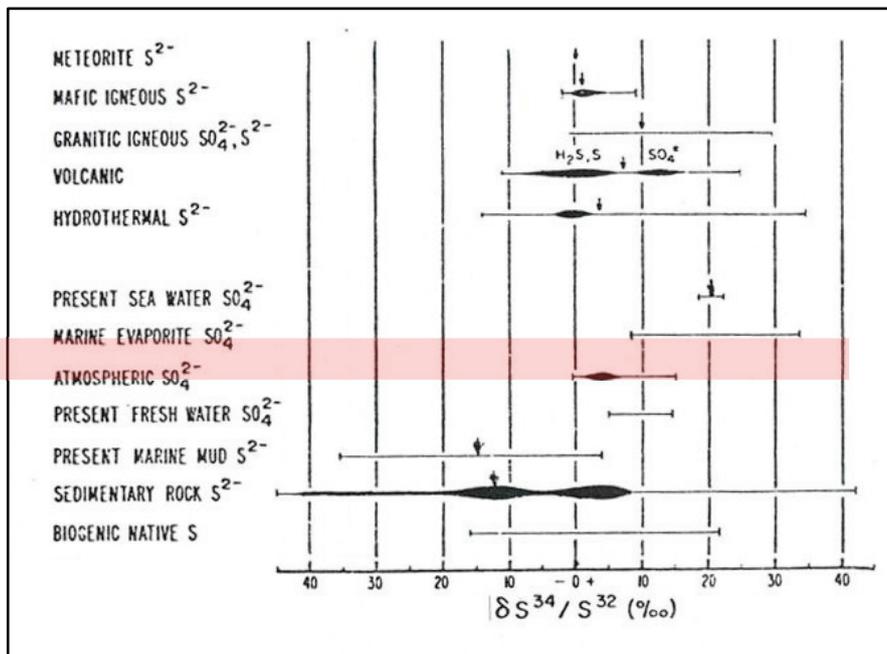


Figure 13. Distribution of $\delta^{34}\text{S}$ in nature (Holser and Kaplan, 1966)

Fluid inclusion microthermometry

Fluid inclusion microthermometry confirms the ore paragenesis suggested by petrography, cathodoluminescence microscopy, and stable isotope O and C signatures. Fluid inclusions in authigenic quartz indicate that the main disseminated stratabound Cu-Co sulphide mineralization event was characterized by relatively hot (mainly between 120°C and 180°C), saline (~8.5 to ~18.5 eq. wt% NaCl) fluids (Dewaele *et al.*, 2006). El Desouky *et al.* (2009) also noticed a general trend of increasing salinities with increasing homogenisation/formation temperatures (Th). This points to a mixing between hot saline metal-bearing brine and colder low-salinity pore fluid.

Stable isotope O and C signatures of the the diffused vein selvages and concordant-discordant veins ('heal' fractures) suggest slightly higher temperatures of formation and/or a meteoric input. Microthermometry indicated temperatures of up to 420°C and salinities between ~37 to ~44 eq. wt% NaCl in these veins (Dewaele *et al.*, 2006 and El Desouky *et al.*, 2009), confirming the stable O and C isotope data.

Resulting mineralization model

Phase I: sediment deposition to early diagenesis

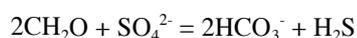
The sedimentation style ranges from basement-proximal detrital siliciclastic sediment in the south-east (Zambia) to basement-distal coastal sabkhas in the north-east (DRC), with a major facies transition occurring in the Konkola area close to the border between Zambia and the DRC. The basement-proximal detrital siliciclastic sediments are of an alkali granitoid source, and this provenance is evident throughout the Lower Roan Formation on the Zambian side.

Sabkha conditions prevailed across a wide carbonate inner ramp on the DRC side, characterized by coastal sabkhas with alternating shallow marine incursions. Evaporitic dolostones formed during dry cycles and/or low sea levels and siltstones during wet cycles and/or high sea levels. Anoxic conditions prevailed within the sabkha lagoons, which were often cut off from fresh sea water influx during dry cycles. This resulted in the preservation of organic carbon and formation and preservation of syngenetic to early diagenetic pyrite. The interbedded pyritic carbonaceous shales common throughout the Lower Roan Formation, especially in the sabkha facies to the west, are prime examples of these. These early diagenetic conditions, in a highly evaporative sabkha environment are also conducive to dolomitization and thus to carbonatization of evaporites. The latter, however, may have been limited as little to no reduction of sulphate sulphur occurred up to this stage.

Phase II: diagenesis to late diagenesis

This phase is characterized by intense carbonatization and dolomitization of the evaporates, probably involving later subsurface dolomitization. This may be confirmed by the presence of magnesite, which is indicative of higher temperatures, suggesting formation at greater depths (Figure 14). The main effect of carbonatization and dolomitization is an increase in porosity (up to 22%) and associated permeability. This was one of the most important stages in preparing the Lower Roan sediments for the metal-bearing mineralizing brine.

The other was the thermochemical reduction (TSR) and/or bacterial sulphate reduction (BSR) that occurred in association with the dissolution of evaporitic sulphates. Thermochemical sulphate reduction usually occurs at temperatures >100°C, and both TSR and BSR require organic carbon, resulting in the following basic reaction:



This reaction produces both CO₂ and H₂S. The addition of CO₂ can also cause carbonate dissolution, which can result in increased porosity.

The host sediments were thus prepared during diagenesis to late diagenesis for the reaction with the oxidizing metal-bearing brine, by:

- An increase in 'secondary' porosity and permeability, due to carbonatization and dolomitization, and sulphate reduction and associated evaporite dissolution
- Filling of the primary and secondary pores with reducing H₂S- and CO₂-rich fluids.

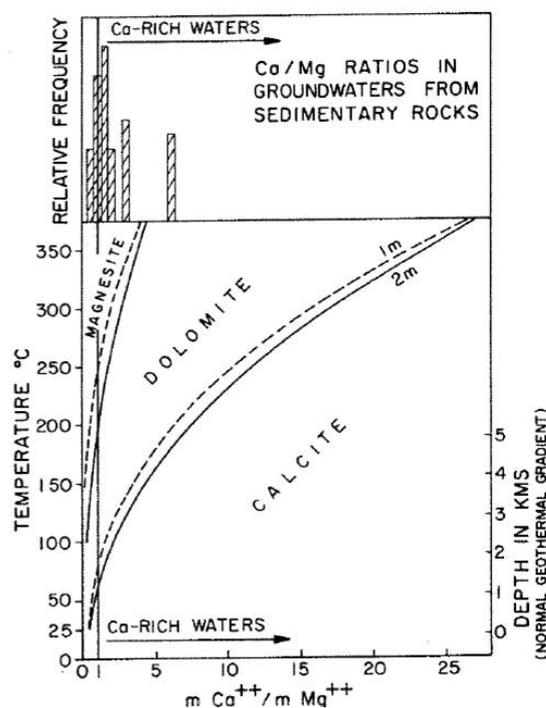


Figure 14. Dolomitization environment with regard to Ca/Mg ratio, temperature, and depth for groundwaters from sedimentary rocks (after Hardie, 1987)

Phase III: hydrothermal mineralizing event

The introduction of an oxidizing Cu-Co metal-bearing brine must take place before secondary porosity and permeability are destroyed by subsequent metamorphic events. The timing of this event is thus critical as the metal-bearing fluid needs to permeate through the sediments, depositing widespread disseminated stratabound mineralization. The metal-bearing brine is probably oxidizing since the solubility of Cu at low temperatures (<200°C) is much higher under oxidizing conditions than under reducing conditions (Figure 15) (Rose, 1976). The footwall rocks, siliciclastic sediments and basement alkali granitoids, to the Roan Formation, with the presence of substantial Fe oxides, are clearly oxidizing in nature and the most probable source of the metal-bearing brines

The deposition of the Cu and Co sulphides then took place upon the mixing of two fluids, namely a reducing H₂S-rich pore fluid hosted within the Lower Roan sediments and an intruding oxidizing Cu-Co metal-bearing brine. The latter most probably originated from the underlying detrital oxidizing basinal sediments. The contribution of the basement granitoids to these metal-bearing brines still needs to be proven, but indications are that it was likely. Granitoid-related iron-oxide-copper-gold (IOGC) mineralization is common in the Lufilian Arc, with alkaline magmatism also present during the various rifting phases that formed the Mesoproterozoic to Neoproterozoic basin (Lobo-Guerrero, 2004). Many of these Lufilian Arc IOGC deposits are also characterized by the presence of substantial Co and U concentrations. These early syn-rifting IOGC deposits could have contributed significantly to the footwall metal content. The metal-bearing basinal brines were probably forced upward into the overlying sediments by the onset of basin dewatering along transecting structures such as faults. These basinal brines are usually driven by compaction of the sedimentary basin as well as the onset of the compressional tectonics, such as the Lufilian orogeny. The hydrothermal phases, which include Cu and Co sulphides, authigenic quartz, and possibly some minor carbonates (dolomite) then filled the open space.

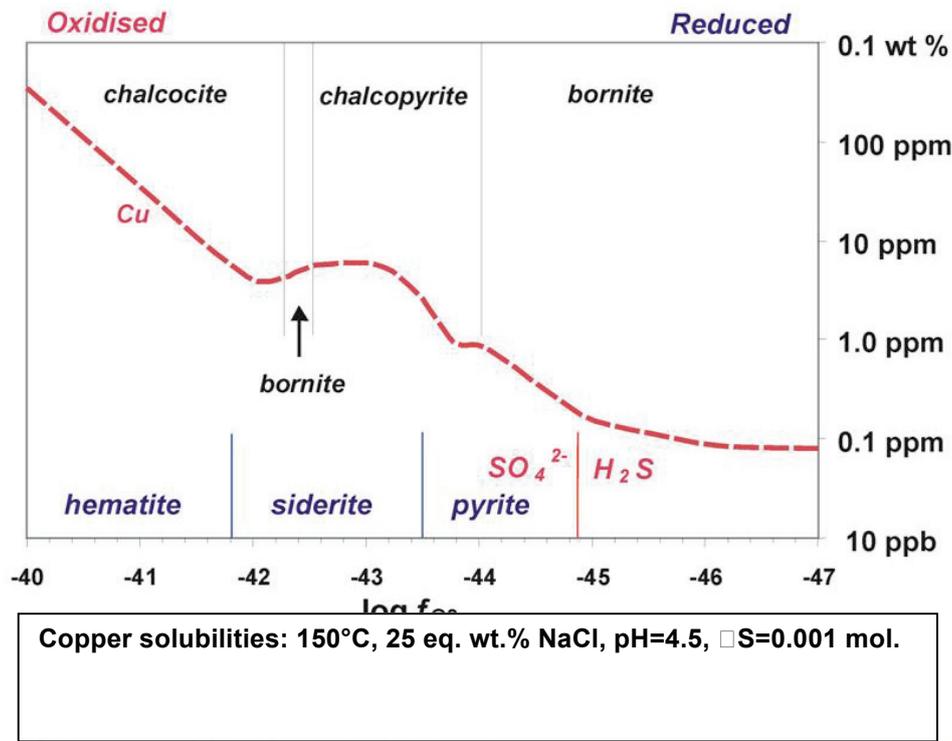


Figure 15. Copper solubility under oxidizing and reducing conditions at 150°C, in highly saline fluids (25 equivalent wt.% NaCl) (after Cooke, 2000)

Phase IV: regional metamorphism

There are indications that peak metamorphism increases from chlorite zone greenschist facies in the north-west to biotite zone greenschist facies in the south-east. Some later structures in the north-west are characterized by localized talc schists, which result from intense alteration of the impure evaporitic dolomites. The metamorphic overprint is also characterized by a concordant-discordant vein system, which is evident of localized closed-system remobilization and redistribution of the material within the Lower Roan ‘Ore Shale’.

Conclusion

The stratigraphic position of Cu-Co mineralization is controlled by the inherent characteristics of the host sedimentary rocks. There is thus a very strong lithological control on the Cu-Co mineralization.

This lithological control was governed by the sedimentary and physiochemical characteristics of the reducing ‘grey bed’ host rock and underlying oxidized ‘red bed’ sediments and alkali granitoid basement, namely:

- Stratabound nature
- Basin-wide occurrence
- Evaporitic sulphates
- Organic carbon
- Dolomitization
- Bacterial reduction (BSR) and/or thermochemical sulphate reduction (TSR)
- Increased secondary porosity and permeability
- Oxidizing metal-rich footwall rocks
- Mixing of two fluids
 - Reducing $H_2S + CO_2$ pore fluids in host rock
 - Oxidizing Cu-Co-bearing brines intruding from underlying footwall rocks at low temperatures ($\pm 100^\circ C$ to $\sim 200^\circ C$)

Later remobilization of the sulphides and associated gangue phases into discordant-concordant veins during the Lufilian orogeny tectonic and metamorphic event is evident throughout the Copperbelt. This event is characterized by higher metamorphic temperatures (up to 420°C).

The Central African Copperbelt thus appears to be a diagenetic to late diagenetic orebody, with a very strong lithological control governing its geological locality and distribution. The main exploration target for primary Cu-Co Copperbelt deposits remains the Lower Roan (Zambia) and equivalent evaporitic horizon in the DRC.

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