Journal of African Earth Sciences 132 (2017) 1–15

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

Sedimentology of the Shangoluwe breccias and timing of the Cu mineralisation (Katanga Supergroup, D. R. of Congo)

Pascal Mambwe [a, b, c, *], Louis Kipata [a], Mumba Chabu [a], Philippe Muchez [c], Toto Lubala [a], Michel Jébrak [d], Damien Delvaux [e]

[a] Department of Geology, University of Lubumbashi, B.P.1825, Lubumbashi, Democratic Republic of the Congo
[b] Department of Geology Exploration, Tenke Fungurume Mining S.A, Route de l'Aéroport, Bâtiment TFM, Commune annexe, Lubumbashi, Democratic Republic of the Congo
[c] KU Leuven, Geodynamics and Geofluids Research Group, Department of Earth and Environmental Sciences, Celestijnenlaan 200E, B-3001, Leuven, Belgium
[d] Department of Earth Science and Atmosphere, Université du Québec à Montreal, H3C3P8, Canada
[e] Department of Geology and Mineralogy, Royal Museum of Central Africa (RMCA), Leuvensesteenweg 13, 3080, Tervuren, Belgium

ARTICLE INFO

Article history:
Received 7 July 2016
Received in revised form
18 April 2017
Accepted 19 April 2017
Available online 20 April 2017

Keywords:
Sedimentary breccias
Lufilian arc
Katanga Supergroup
Copper mineralisation
Shangoluwe

ABSTRACT

The origin of breccias in the Neoproterozoic Katanga Supergroup in D.R of Congo is still a matter of debate. At the Shangoluwe Cu deposit located in the Kambove mining district (central part of the Lufilian arc), the sedimentary breccias bearing Cu mineralisation have been investigated for lithological and sedimentological study, quantitative analysis of the breccias fragments and fault kinematic analysis in order to understand the origin of the breccias, their lithostratigraphic position and the timing of mineralisation.

At Shangoluwe, three sedimentary breccias sequentially deposited within the Kundelungu rocks can be identified on the basis of the nature of the matrix and fragments; from bottom to the top, the Ferruginous Breccias, the Dolomitic Breccias and the Siliceous Breccias. These breccias were deposited as lenses. The presence of debris and grain flows, a finely laminated matrix, pseudo-stratification, normal and reverse graded-bedding, and the presence of interbedded siltstone, sandy shale, dolomitic shale, shale and dolomite, are considered as evidence of a sedimentary origin of the breccias. The log normal distribution of the fragments indicates that gravity flow was the main deposition mechanism.

The Ferruginous and Dolomitic Breccias are regarded as contemporaneous with the Kundelungu Group. They were deposited as lenses interbedded in the Kanianga and Mongwe formations, both affected by the Lufilian orogeny (D1 - Kolwezian and D2 – Monwezian phases). The Siliceous Breccias are post-orogenic as shown by the presence of an erosional and angular unconformity respectively on the Dolomitic Breccias and the Kundelungu formations. Therefore, the Siliceous Breccias are attributed to the Lower Palaeozoic Biano Subgroup and the lithostratigraphy of the Biano Subgroup is proposed for revision accordingly. Copper mineralisation post-dates the deposition of the breccias, the dissolution of dolomite fragments and in-situ fragmentation. This mineralisation occurred during late- to post-orogenic extension of the Lufilian orogeny, and was remobilised during the Cenozoic.

1. Introduction

The Katanga Supergroup is formed of sedimentary and meta-sedimentary rocks that crop out within the Katanga Copperbelt that extends from the SE Democratic Republic of the Congo to the northwestern and western part of Zambia. The Katanga Supergroup hosts world-class Cu-Co stratabound deposits (François, 1973, 1974; Cailteux, 1994; Cailteux and Misi, 2007; El Desouky et al., 2009; Hitzman et al., 2010; Muchez et al., 2015). The Katanga Copperbelt shows two contrasting structural domains, the folded Katangan or Lufilian arc and the tabular Katangan or Katangan foreland to the north of the belt (Fig. 1). The folded Katangan contains most of the important Cu-Co deposits hosted in the Roan group and Cu-Pb-Zn mineralisation in the Nguba Group (François, 1973; Chabu, 1995; Kamona et al., 1999; Kampunzu et al., 2009; Hitzman et al., 2010;

---

* Corresponding author. Department of Geology, University of Lubumbashi, B.P.1825, Lubumbashi, Democratic Republic of the Congo.
E-mail address: p.mambwe@sciencesunilu.ac.cd (P. Mambwe).

http://dx.doi.org/10.1016/j.jafrearsci.2017.04.017
1464-343X/

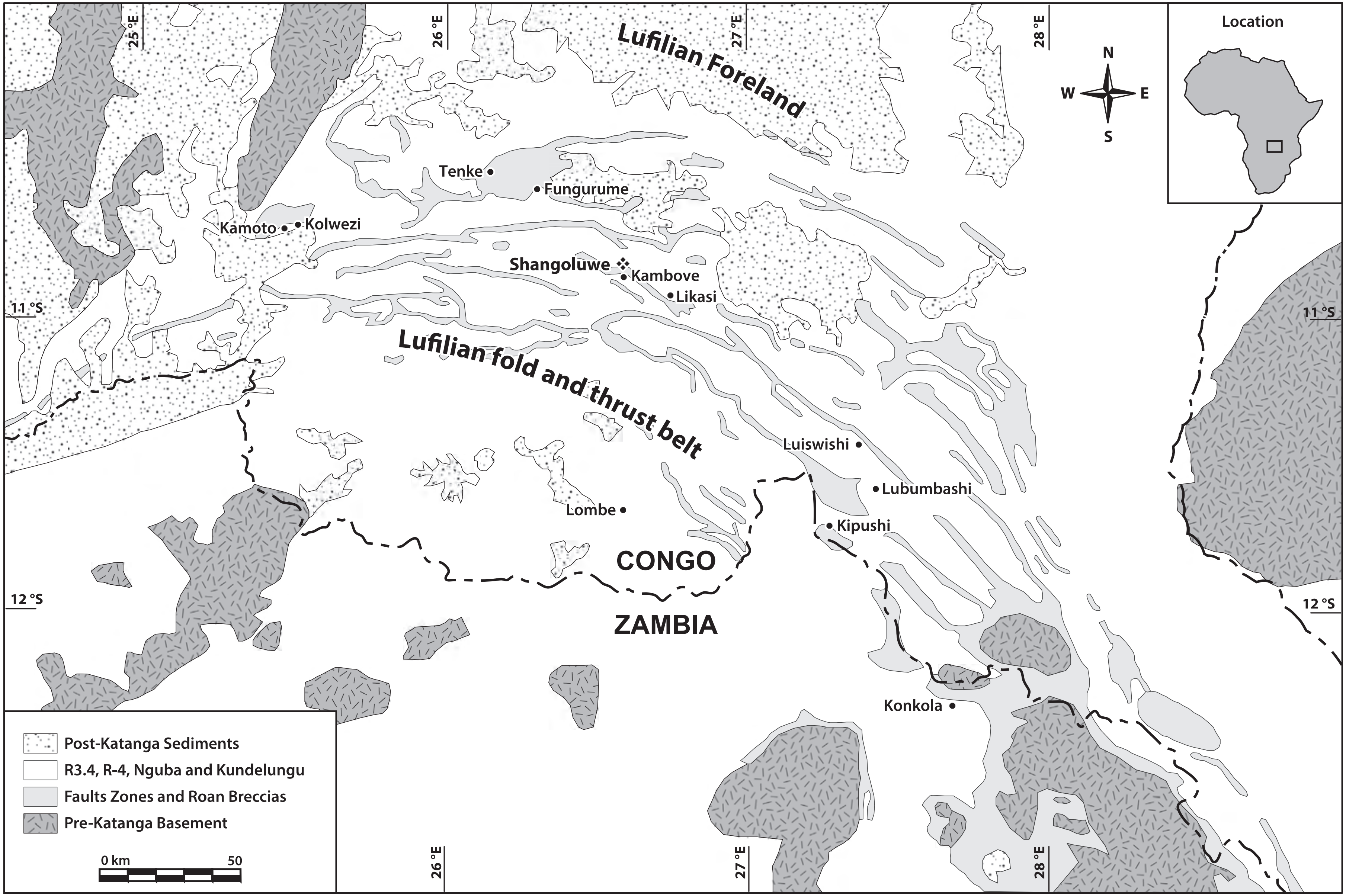

Fig. 1. Geological and tectonic framework of the Lufilian arc, Kundelungu foreland and Kibaran belt and surrounding regions with structural subdivision of the Lufilian arc (after Kampunzu and Cailteux, 1999).

Mambwe et al., 2017). Within the tabular Katangan, the mineralisation includes some vein-type Cu-Ag hosted in the Kundelungu Group and stratiform Cu hosted in both Nguba and Kundelungu groups (El Desouky et al., 2007, 2008a, b; Haest et al., 2007).

Several types of breccias and conglomerates were described in both the Congolese side of the Katangan belt (Congo Copperbelt) and Zambian side (Zambia Copperbelt) but their origin remains a matter of debate (François, 1973, 2006; Binda and Mulgrew, 1974; Grujenschi, 1978; Okitaudji, 1992; Binda and Porada, 1995; Cailteux and Kampunzu, 1995; Jackson et al., 2003; Wendorff, 2000a, b; 2005a, b, 2011). In the Congo Copperbelt, Cu-Pb-Zn mineralised breccias at Kipushi were interpreted as evaporitic collapse breccias (De Magnée and François, 1988; Chabu and Boulègue, 1992). The megabreccia with fragments of the Roan, Nguba and Kundelungu groups are interpreted as part of thick tectonic sheets which formed during the main phase of the Lufilian orogeny (Okitaudji, 1992; Cailteux and Kampunzu, 1995; Jackson et al., 2003). The Mines Subgroup megabreccia consists of hundreds of meters to kilometer long fragments and they contain the main Cu-Co mineralisation (Cailteux, 1994; François, 2006; Schuh et al., 2012). Grujenschi (1978) interpreted these megabreccias as wildflysches in the Katanga sedimentary basin and Wendorff (2000a, b, 2003, 2005a, 2011) considered the megabreccias as olistostrome deposits in the Fungurume foreland basin and therefore also as younger than the Kundelungu Group.

At Shangoluwe, the precipitation of copper minerals in the breccias was mentioned by Cailteux and Dessart (1984) and François (2006), but without any details on the relationship with the host rock, depositional setting and tectonic deformation. Copper mineralisation in the Kundelungu Group surrounding the Shangoluwe breccias has not been reported by previous studies. The Shangoluwe breccias were not considered in recent studies that focussed on descriptive models, grade-tonnage relationship, assessment of sediment-hosted copper deposits and regional stratigraphic correlations of the Neoproterozoic Katanga Supergroup in the Congo Copperbelt (Hitzman et al., 2012; Taylor et al., 2013; Zientek et al., 2014).

In this work, we investigate the structural, lithological and sedimentological aspects of the Shangoluwe breccias hosted within the Kundelungu rocks. The aims of this paper are to understand the origin of the Shangoluwe breccias and their lithostratigraphic position. The Cu mineralisation hosted in these breccias and surrounding Kundelungu rocks is discussed in terms of the timing of precipitation. The paper also discusses the relationship between the formation of the breccias and the brittle tectonic evolution within the Congo Copperbelt.

2. Geological setting

2.1. Lithostratigraphy of the Katanga Supergroup

The Neoproterozoic Katanga Supergroup consists of a ~10,000 m-thick sequence of sedimentary and metasedimentary rocks. It was deposited in an extensional setting during the Neoproterozoic and subsequently deformed during the Lufilian orogeny as a consequence of the interaction between the Congo and the Kalahari cratons (Porada and Berhorst, 2000) during the amalgamation of the Pan-African Gondwana supercontinent (Grantham et al., 2003; De Waele et al., 2008). This supergroup is divided into three groups, based on the occurrence of two regional diamictites: Roan, Nguba and Kundelungu groups from bottom to the top (François, 1973, 2006; Cailteux et al., 1994, 2007; Batumike et al., 2007). The Roan and Nguba groups are separated by the Grand Conglomérat diamictite or Mwale Formation (Ng 1.1) at the base of the Nguba Group. The Petit Conglomérat diamictite or Kyandamu Formation (Ku 1.1) at the base of the Kundelungu Group forms the boundary between the Nguba and Kundelungu groups (Table 1).

The Roan Group is stratigraphically well-known because it contains important Cu-Co mineralisation. It is subdivided into four subgroups: RAT (R1), Mines (R2), Dipeta (R3) and Mwashya (R4) subgroups (Cailteux et al., 2005a, 2007). The Mines Subgroup consists of alternating siltstone, carbonaceous dolomitic shale and dolomite. It is subdivided into three formations: Kamoto (R 2.1), Dolomitic shale (R 2.2) and Kambove (R 2.3). Three Cu-Co orebodies are known within the Mines Subgroup; the Lower orebody hosted in the Kamoto Formation, the Upper orebody hosted in the Dolomitic Shale Formation and a third orebody (not always present) at the lower part of the Kambove Formation (Kampunzu et al., 2009).

The Shangoluwe deposit is one of the Cu-(Pb-Zn) deposits hosted in the Kundelungu Group. It is located along the NW-SE regional M'sesa fault, which crosscuts the Kambove synform (Fig. 2). The mineralisation at Shangoluwe is stratabound and hosted in breccias and surrounding Kundelungu Group rocks. The deposit is structurally divided into three zones (North, Central and South) separated by transverse sinistral faults (François, 2006; Kipata, 2013). The deposit was discovered in 1931 by the 'Union Minière du Haut-Katanga'. A total of 1,030,627 tons of ore with an average grade of 9.63% Cu were mined between 1933 and 1943 by open pit and underground operations (Cailteux and Dessart, 1984).

2.2. Lufilian and post-Lufilian geodynamics

The Lufilian orogeny operated within three major tectonic phases (François, 1974, 2006; Kampunzu and Cailteux, 1999). As a result of this orogeny, the Katangan belt presents two contrasting tectonic domains, the folded Katangan belt referred to as Lufilian arc due to its arcuate shape and the undeformed Katangan belt or Katangan foreland to the north of the belt. The first phase (D1) or Kolwezian phase is characterised by northward verging folds and thrust sheets. It is coeval with the main deformation phase in the Zambezi belt. The second phase (D2) or Monwezian phase generated large left-lateral strike-slip faults. The last phase (D3) or Shilatembo phase is marked by structures transverse to the trend of Lufilian arc.

On the basis of a regional fault-kinematic and palaeostress investigation in the Congo Copperbelt, Kipata et al. (2013) defined eight brittle tectonic stages. These brittle events range from the onset of the brittle realm during the Lufilian orogeny paroxysm (~530 Ma) to post-orogenic periods. The first five brittle stages (1–5) are related to the Lufilian orogeny, from its paroxysm to the final post-orogenic extension. The stages 1 and 2 correspond to the Kolwezian phase (D1) of Kampunzu and Cailteux (1999) and the Stage 3 is correlative to the Monwezian phase (D2) of the same authors. The sixth stage corresponds to the Shilatembo phase (D3) of Kampunzu and Cailteux (1999) and is considered by Kipata et al. (2013) as related to post-Lufilian (Early Mesozoic?) transpressional inversion. The two last stages (7th and 8th) are related to late Cenozoic rifting of the East African Rift System.

3. Petrography and ore mineralogy

In the Shangoluwe deposit, the breccias are dominantly constituted by fragments belonging to the Roan and Kundelungu groups. The Kanianga Formation (Ku 1.3) is recognised in the Shangoluwe North and Central, whereas the Mongwe Formation (Ku.2.1) crop out in the Shangoluwe South (François, 2006; Kipata, 2013).

3.1. Kanianga Formation (Ku 1.3)

The Kanianga Formation (Ku 1.3) is made up of alternating green laminated dolomitic shales, grey shales, grey dolomitic sandy shales, blackish grey massive dolomite and stratified dark grey dolomite (Fig. 3A and B). All of these lithologies are weathered into a brownish argillaceous rock with sericite, chlorite and black manganese oxides. On thin sections, muscovite is mainly associated with dolomite crystals, chlorite, authigenic quartz and detrital coarse quartz grains in the dolomitic sandy shales. Veins of pyrite-chalcopyrite-chalcocite-dolomite-quartz are usually observed.

The stratified dark grey dolomite is characterised by a parallel bedding and dissemination of fine- to coarse-grained euhedral pyrite. Under the microscope, this rock is formed by rhombohedral dolomite crystals with occasional muscovite flakes. Dominant copper sulphides include bornite, chalcopyrite and chalcocite, locally oxidised into malachite and chrysocolla, but azurite is found occasionally in pores and fractures.

3.2. Mongwe Formation (Ku 2.1)

The Mongwe Formation (Ku 2.1) consists of greenish grey argillaceous dolomitic sandy shales within laminated grey shale layers. Under the microscope, the argillaceous dolomitic sandy shale is formed of fine- to coarse-grained quartz crystals, dolomite, muscovite, biotite and chlorite. The main sulphides are pyrite, chalcopyrite and bornite, but occasionally supergene minerals such as malachite and chrysocolla occur in association with the sulphides. They are observed in pores and fractures together with authigenic quartz, hematite and goethite.

The laminated grey shale layers weathered into a clayey rock characterised by the presence of hematite and goethite along bedding planes and in fractures, while chrysocolla is more abundant than malachite (Fig. 3C).

3.3. Breccias

According to Morrow (1982) and Jébrak (1997), breccias can be classified based on the nature of the matrix, lithology, structure, texture, fragment maturity, deformation and mechanism of formation. At Shangoluwe, three types of breccias were distinguished based on the nature of the matrix and lithology; Ferruginous, Dolomitic and Siliceous Breccias.

3.3.1. Ferruginous Breccias

These Ferruginous Breccias (Fig. 3D) are made up of millimetric to centimetric (up to 50 cm) fragments of massive and laminated siliceous dolomite, black dolomite ("dolomie tigrée"), stratified grey dolomite, massive grey to black sandy dolomite and massive grey siliceous dolomite. The matrix is an iron-rich sandy clay consisting of quartz, hematite and clay minerals.

On thin sections coarse-grained and authigenic quartz are associated with equal sized dolomite in a clay-rich matrix. Disseminated euhedral pyrite is found in dolomite fragments, whereas framboidal pyrite is associated with chalcopyrite and bornite, both within the matrix and fractures. Pyrite has been replaced locally by hematite. Goethite and hematite are prominent mineral phases and give the breccias a brownish red color. Azurite, chalcocite, chrysocolla, covellite and malachite are the common supergene minerals.

Table 1
Lithostratigraphy of the Neoproterozoic Katanga Supergroup (Batumike et al., 2007; Cailteux et al., 2007) including the sedimentary breccias studied in this paper. Ages are from Hanson et al. (1993), Key et al. (2001), Armstrong et al. (2005) and Master et al. (2005).

Supergroup	Group	Subgroup	Formation	Members & lithologies
±570 Ma	Kundelungu Ku	Biano Ku 3		Arkoses, conglomerates, argillaceous sandstones, sedimentary breccias
		Ngule Ku 2	Sampwe - Ku 2.3	Dolomitic pelites, argillaceous to sandy siltstones
			Kiubo - Ku 2.2	Dolomitic sandstones, siltstones and pelites
			Mongwe - Ku 2.1	Dolomitic pelites, siltstones, sandstones and sedimentary breccias
		Gombela Ku 1	Lubudi - Ku 1.4	Pink oolitic limestone
			Kanianga - Ku 1.3	Carbonate siltstones, shales and sedimentary breccias
			Lusele - Ku 1.2	Pink to grey micritic dolomite (Calcaire Rose)
±635Ma			Kiandamu - Ku 1.1	Petit Conglomérat tillite/diamictite
	Nguba Ng	Bunkeya Ng 2	Monwezi - Ng 2	Dolomitic sandstones, siltstones and pelites
			Katete - Ng 2.1	Dolomitic sandstones or siltstones in northern facies; alternating shale and dolomite beds ("Série Récurrente") in southern facies
		Muombe Ng 1	Kipushi - Ng 1.4	Dolomite with dolomitic shale beds
			Kakontwe - Ng 1.3	Carbonates
			Kaponda - Ng 1.2	Carbonate shales and siltstones; dolomie Tigrée at the base
±765 ± Ma			Mwale - Ng 1.1	Grand Conglomérat tillite/diamictite
	Roan R	Mwashya (formerly Upper Mwashya) R 4	Kanzadi - R 4.3	Sandstones or alternating siltstones and shales
			Kafubu - R 4.2	Carbonaceous shales
Katangan			Kamoya - R 4.1	Dolomitic shales, siltstones, sandstones, including conglomeratic beds and cherts in variable position
		Dipeta R 3	Kansuki - R 3.4	Dolomites including volcaniclastic beds (formerly Lower Mwashya)
			Mofya - R 3.3	Dolomites, arenitic dolomites, dolomitic siltstones
			R 3.2	Argillaceous to dolomitic siltstones with interbedded feldspathic sandstones or white dolomites; intrusive gabbros
			RGS - R 3.1	Argillaceous dolomitic siltstones (R.G.S., "Roches Gréso-Schisteuses")
		Mines R 2	Kambove - R 2.3	stromatolitic, laminated, shaly or talcose dolomites; locally sandstones at base; beds of siltstones at top
			Shales Dolomitiques - R 2.2	Dolomitic shales including three carbonaceous horizons; occasional dolomites
			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.)
833 ± 10 Ma		R.A.T. R 1		Red argillaceous dolomitic siltstones and sandstones ("Roches Argilo-Talqueuses")
	Base of the R.A.T. sequence unknown			
<900 Ma				Basal conglomerate

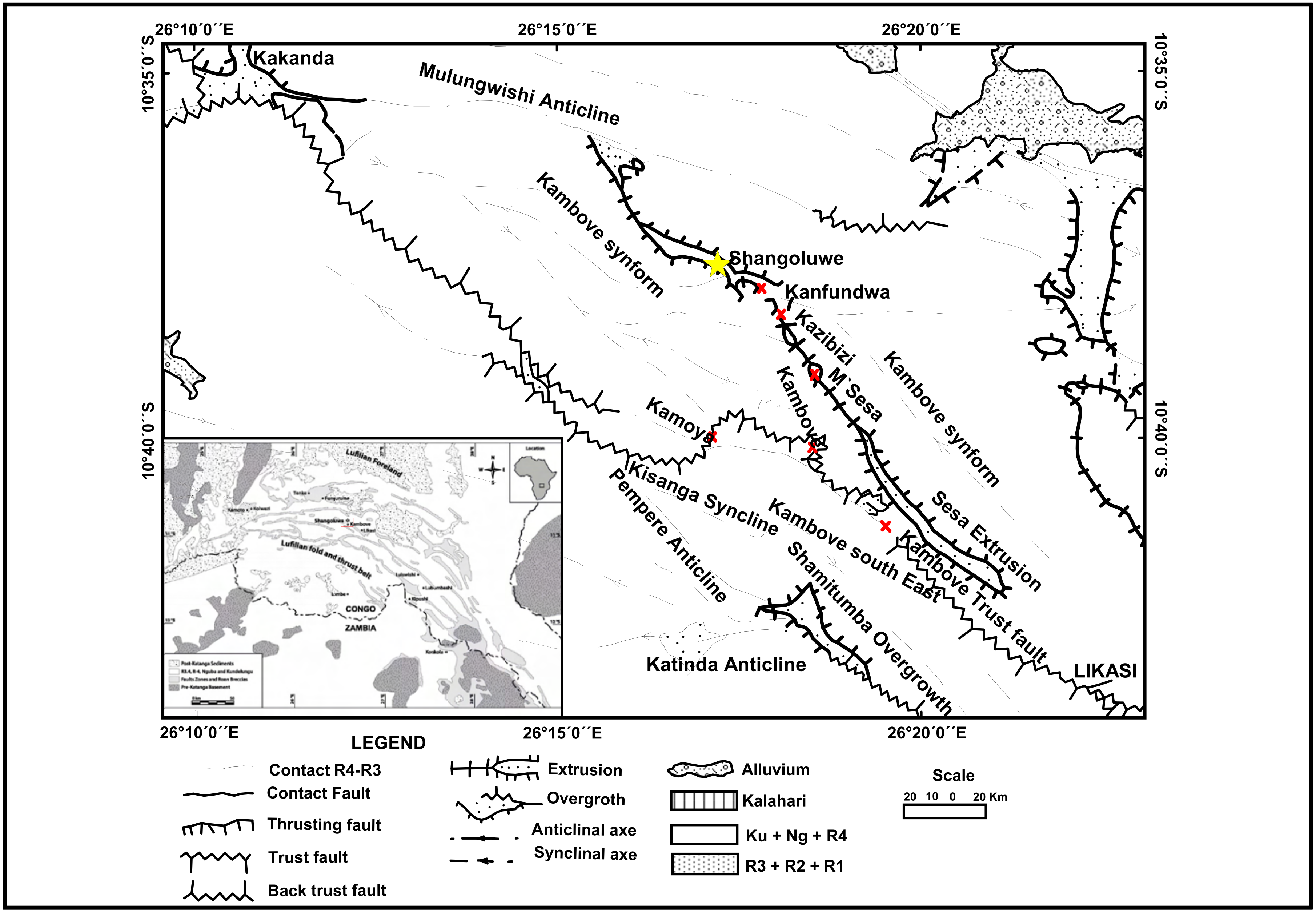

Fig. 2. Location of the Shangoluwe Cu deposit and the geology of the Kambove region (François, 2006).

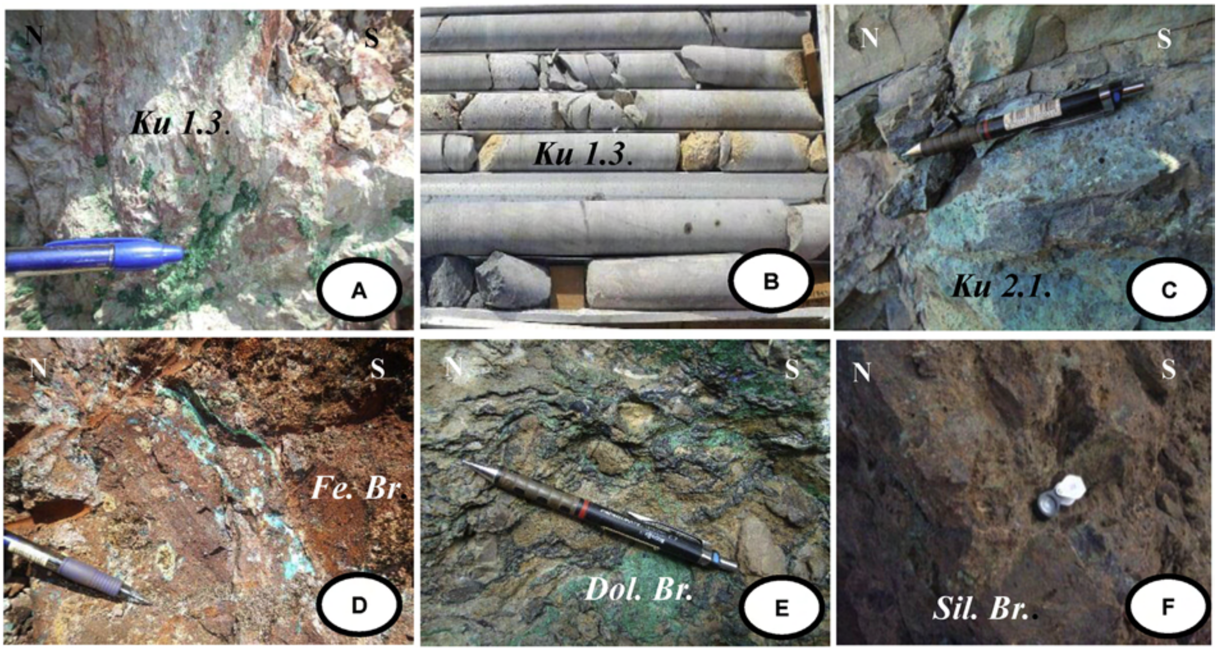

Fig. 3. Kundelungu rocks and Shangoluwe breccias. A: Fractured dolomitic shale (Kanianga Formation-Ku 1.3), B: Pyritic dolomite (Kanianga Formation-Ku 1.3), C: Argillaceous sandy dolomitic shale (Mongwe Formation-Ku 2.1), D: Ferruginous Breccias (Fe.Br.), E: Dolomitic Breccias (Dol.Br.), F: Siliceous Breccias (Sil.Br.).

3.3.2. Dolomitic Breccias

The Dolomitic Breccias are characterised by a massive siliceous matrix (Fig. 3E). Dolomite fragments are also millimetric to centimetric (up to 50 cm) with color varying from light-grey to dark-grey. Azurite, malachite, chrysocolla, chalcocite, covellite, sphalerite and galena are found in the matrix and in fractures. They

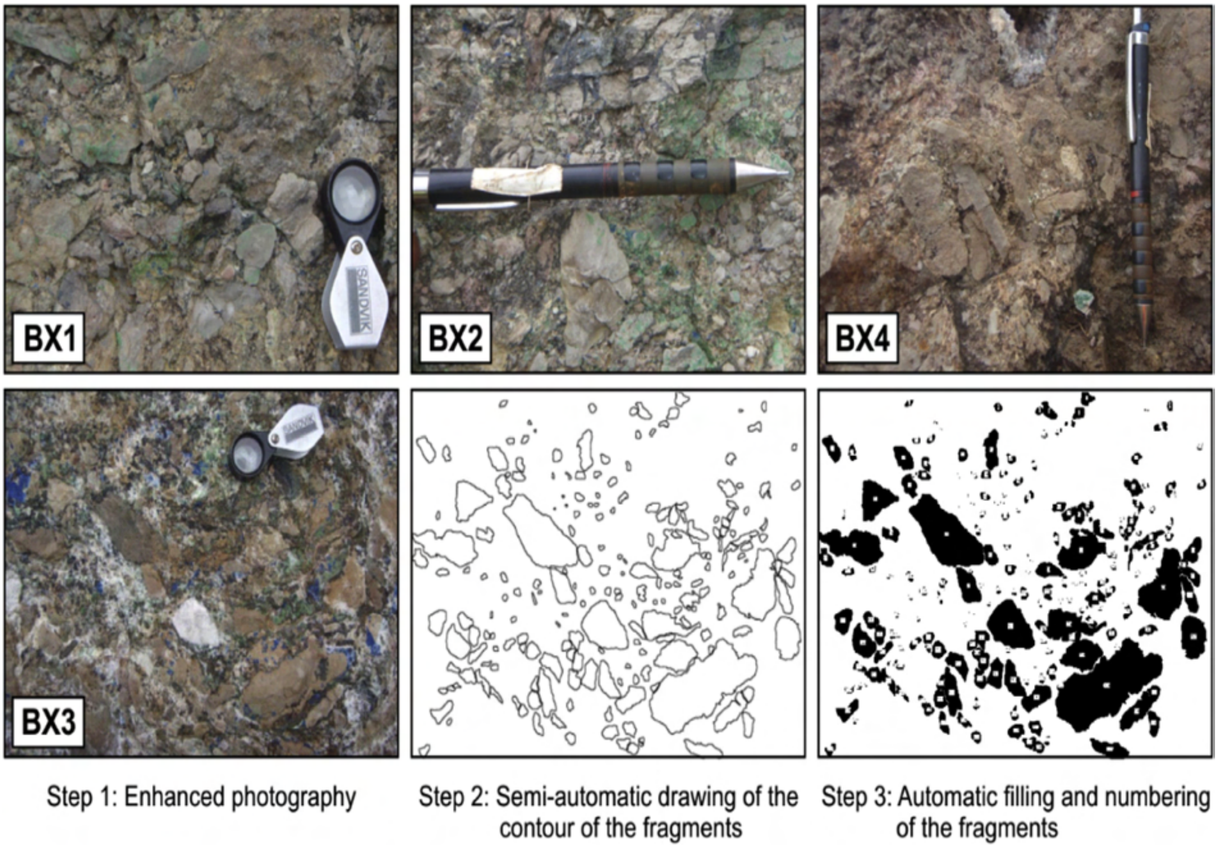

Fig. 4. Field photographs used for the quantitative analysis of the Shangoluwe breccias: BX1, BX2, BX3 (Dolomitic Breccias) and BX4 (Ferruginous Breccias).

are associated with neoformed quartz grains and occasional muscovite, goethite and dolomite. The dissolution of dolomite fragments has produced deeply weathered carbonate minerals associated with authigenic quartz.

3.3.3. Siliceous Breccias

The Siliceous Breccias contain deeply weathered dolomite fragments in a recrystallised siliceous matrix (Fig. 3F). Dolomitic fragments are millimetric to centimetric (up to 80 cm) in size and weathered into yellowish and brownish argillaceous rocks. Malachite and barite are present in dissolution cavities and pores of altered fragments. The breccias are massive or characterised by a finely laminated matrix containing spots of malachite. On thin sections altered dolomite is associated with muscovite and newly formed quartz. Carbonate residues fill micropores left between granular quartz grains. Disseminated chalcopyrite, bornite and pyrite occur in the recrystallised siliceous matrix and in fractures.

4. Quantitative analysis of the breccias

4.1. Methodology

The methodology for breccias analysis is based on the quantitative approach developed by Jébrak (1997), Bérubé and Jébrak (1999) and Lorilleux et al. (2003). In this study, four representative photographs were analysed after contrast enhancement, manual extraction using a Wacom tablet, and geometric fragment analysis using the Image-J public domain software. Only fresh and slightly weathered outcrops were selected for this analysis because it was not possible to recognise the fragment contour on deeply weathered outcrops. The Siliceous Breccias were not considered for the quantitative analysis because they are intensely weathered into clay or clayey rock.

Five main parameters were recorded: the particle size distribution (PSD), aspect ratio, circularity, area/perimeter ratio, and fragment solidity. The interpretation of the data is based on the style of initial fragmentation, fragmentation process and transportation.

The style of initial fragmentation is evaluated using PSD analysis. In isotropic rocks, normal PSD corresponds to the formation of semi-equal fragments that show a regular fragmentation pattern. Such pattern is characterised by a low energy fragmentation process such as desiccation, cooling, or extension with a low differential stress (Jébrak, 1997). It could also result from a late sorting of the fragments by a dynamic process, such as water transportation. A log normal to fractal distribution indicates an early focalisation of the fragmentation and results from a high energy process such as explosion or seismic process. Fragmentation processes are investigated by studying the evolution of the geometric parameter of the fragments. Transportation processes after fragmentation are described by geometric parameters related to the shape of the fragments: solidity and circularity are the expression of the shape complexity; low circularity (0.1) and low solidity (0.5) indicate a very complex shape. The area/perimeter ratio is also an expression of the complexity. The particle aspect ratio gives the shape factor, i.e. the ratio between length and width of the fragment.

4.2. Results

The results of the quantitative analysis are shown on Figs. 4 and 5 and listed in Table 2. The quantitative analysis of the Ferruginous Breccias indicates that the PSD of the fragments is weakly dispersed, indicating a high level of maturity. Long fragments (aspect ratio up to 9) are progressively cut into smaller pieces and become progressively rounded. The quantitative analysis of the Dolomitic Breccias indicates that the PSD of the fragments is more dispersed, reflecting a lower level of maturity. The long fragments are similar to those observed in Ferruginous Breccias, but less abundant.

The high aspect ratio suggests a later in-situ fragmentation after deposition of the sedimentary breccias, possibly during the main tectonic stages of the Lufilian orogeny. The in-situ fragmentation is followed by dissolution of dolomite fragments. The low value of the area/perimeter ratio (<0.05) is recognised in the Dolomitic Breccias. It is not dependent of the aspect ratio, which suggests that there is no relationship between fragmentation and dissolution of the dolomite fragments at Shangoluwe.

The PSD of the Ferruginous and Dolomitic Breccias has a log normal distribution which suggests formation by high energy processes (Fig. 5E; Table 2) such as gravity flow which is proposed as the trigger mechanism for Shangoluwe breccias deposition. This indicates the absence of a low energy environment at Shangoluwe which is typical for breccias induced by a hydrothermal process such as fluid–assisted brecciation, or volume reduction or expansion (Jébrak, 1997).

5. Sedimentology of the breccias

The three types of breccias are characterised by their texture and internal clast organisation.

5.1. Morphology of the clasts

Quantitative macroscopic analysis and microscopic observations indicate that the shape of the dolomite fragments are very angular to sub-angular (low sphericity), but some are sub-rounded due to dissolution after deposition (Fig. 4). Their size varies between a few mm and 80 cm. These fragments are characterised by in-situ fragmentation, likely during the Lufilian orogeny (cf. quantitative analysis). The dolomite fragments are poorly sorted and supergene Cu minerals such as azurite, chrysocolla, chalcocite, covellite and malachite are found in the cavities. These observations suggest that these breccias are immature, with a short distance transport of the fragments.

5.2. Turbidity current

A series of observations at the Shangoluwe North deposit on outcrops and drill cores indicate that the sedimentary breccias were deposited through turbidity currents.

5.2.1. Intercalated layers in breccias and graded-bedding

The stratified greenish grey siltstones and sandy shales intercalated in the Ferruginous Breccia are altered into brown or red argillaceous rocks. These siltstones and sandy shales (8–10 m thick) were also deposited at the contact between the Ferruginous and Dolomite Breccias (Fig. 6). They were intercepted by drill holes Shan 0071, Shan 0072, Shan 0073, Shan 0074, Shan 0075, Shan 0134 and Shan 0290 (Schuiling, 1940; Cailteux and Dessart, 1984).

In the Dolomitic Breccias, layers of grey to brownish shale mineralised in chalcocite (~1 m thick), grey dolomitic shale (~1 m thick), blackish grey massive dolomite (~1 m thick) and stratified dark grey dolomite (~0.1–2 m thick) were intersected by drill holes SG 0030, SG 0076, SG 0077 and SG 0078 (Fig. 7A). Drill hole SG 0029 intercepted the same breccia alternating with a stratified dark grey dolomite (~10 cm thick), a grey dolomitic shale (10–20 cm thick) and a grey to pinkish shale (~30 cm thick). The petrographic composition of these layers is similar to that of the surrounding Kundelungu rocks.

A normal graded-bedding is observed in both the Ferruginous and Dolomitic Breccias. The Dolomitic Breccias starts with a basal

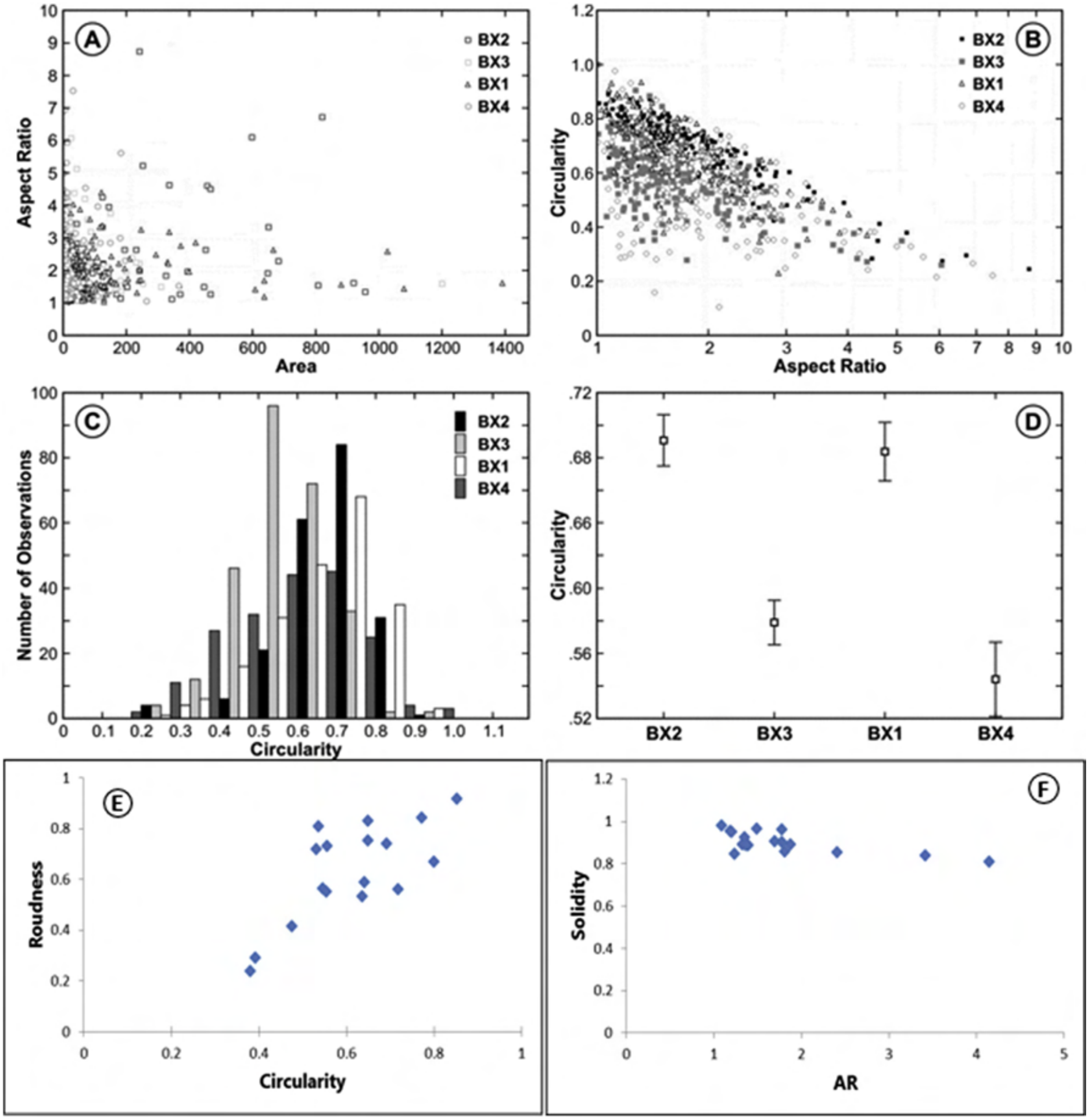

Fig. 5. Quantitative analysis of the Shangoluwe breccias: A: Evolution of aspect ratio and area with the decreasing size; B: Evolution of aspect ratio and circularity; C: Histograms of circularity parameter for the four studied breccias; D: Moustache diagram for the circularity; E: Distribution log normal of dolomite fragment; F: Solidity versus aspect ratio.

4 m-thick layer containing decametric clasts, followed by a layer containing medium-sized clasts (<10 cm diameter) and a top layer characterised by smaller clasts with sizes ranging from few millimeters to centimeters. In the Shangoluwe Central and South deposits a succession of normal and reverse graded-bedding is also observed in some layers (1–2 m thick).

5.2.2. *Pseudo-stratification and finely laminated matrix*

Dolomite layers (~0.5 cm thick) and irregular stratification planes (~0.2 cm thick) occur in both the Ferruginous and Dolomitic Breccias. They contain supergene copper mineralisation such as malachite, azurite and chalcocite. The thickness of each layer in these breccias varies between 10 cm and 1.20 m. Most fragments are oriented parallel to these irregular stratification planes forming

Table 2
Parameters resulting from the quantitative analysis according to the approach of Jébrak (1997), Bérubé and Jébrak (1999) and Lorilleux et al. (2003).

Parameters	Bx1: Dolomitic Breccias	Bx2: Dolomitic Breccias	Bx3: Dolomitic Breccias	Bx4: Ferruginous Breccias
Aspect ratio (AR)	1,3	Numerous long early fragments	1,3	Large distribution with long early fragments
Solidity	0,93	0,9	0,93	0,84
Circularity	0,68	0,68	0,54	0,58
P/A	0,8	0,8	1,8	2,6
Remarks	Circularity increases and AR decreases		AR remains stable	
Results	Low maturity, high circularity, low P/A et high dispersion	Low maturity, high circularity, low P/A et high dispersion	Low mature, low circularity, high P/A, and low dispersion	High maturity, low circularity, high P/A. low solidity et low dispersion

a pseudo-stratification in Ferruginous and Dolomitic Breccias (Fig. 7B). This pseudo-stratification is often parallel to the bedding of the Kanianga and Mongwe formation rocks. The Siliceous Breccias are characterised by a recrystallised and finely laminated siliceous matrix. The dolomitic fragments are weathered into a clayey rock or soft clays (Fig. 7C).

5.3. *Mud flow and continuity of sedimentation*

In the Shangoluwe Central deposit, a red argillaceous layer (~3 m thick) is present at the contact between the Kundelungu sequence and the Ferruginous Breccias. It consists of small dolomite fragments (<1 mm diameter) in an argillaceous matrix. On thin sections the rock contains abundant muscovite, quartz and hematite. The argillaceous layer is interpreted as a mud flow. However, in the northern and southern part of the deposit, a unit (>2 m thick) consisting of alternating shales (2–10 cm thick) and Ferruginous Breccias is observed. The transition between shale and breccias is progressive and characterised by an apparent continuous sedimentation.

5.4. *Grain and debris flow deposits*

The Siliceous Breccias contains massive breccias (~8 m thick) at its base, followed successively by finely laminated breccias (~4 m thick) with clasts oriented parallel to the pseudo-stratification and by a unit consisting of clast-supported breccias (~8 m thick). At the top, the Siliceous Breccias (~5 m thick) is not cemented and the fine-grained matrix is also absent (Fig. 7D). The interaction between different clasts is occasionally observed on the surface of the clasts by the presence of shock marks. This stratigraphic succession and the sedimentological characteristics recognised in the Siliceous Breccias are typical of grain flow deposit as discussed by Lowe (1979) and Cojan and Renard (2006).

Although some layers of the Dolomitic and Ferruginous Breccias are characterised by turbidity currents (e.g. siltstone and sandy shale layers), other layers are characterised by a poor correlation between clast size and bed thickness, an inverse or inverse-to-normal grading with a cohesive matrix, and these layers are sometimes associated with a mud flow (e.g. northern part of the Shangoluwe). Therefore, these two breccias were most likely deposited by debris flows.

6. Structural analysis

The structural analysis was carried out on the breccias and surrounding Kundelungu rocks at Shangoluwe North, Central and South in order to constrain the relative age of the different hypogene sulphide veins.

6.1. *Folding and faulting*

Folding is related to the Kolwezian deformation phase D1 (Kampunzu and Cailteux, 1999) or brittle deformation stages 1–2 of Kipata et al. (2013) affecting both the breccias (Ferruginous and Dolomitic Breccias) and surrounding Kundelungu sequence. Drag folds, inclined folds, overthrust folds and southwest verging recumbent folds were identified in the Shangoluwe area (Fig. 8A–D). Four different fault and fracture sets were identified in the Shangoluwe North deposit by Kipata et al. (2013, site Kat 16). The first set (brittle stage 1 of Kipata et al., 2013) comprises thrust faults and fractures formed under NNW-SSE compression, affecting the Kanianga Formation and the Ferruginous and Dolomitic Breccias. The second set (brittle stage 3 of Kipata et al., 2013) consists of strike-slip fault planes and fractures which formed in a strike-slip context with NE-SW horizontal compression. The third set (brittle stage 5 of Kipata et al., 2013) comprises normal fault planes with a slight strike-slip component which reactivated the contact between the Ferruginous Breccias and the Kundelungu rocks during the post-orogenic E-W extension. The last set (brittle stage 6 of Kipata et al., 2013) corresponds to bedding plane reactivations with sub-horizontal slip lineations coated with black and pink Fe-oxides, corresponding to the far-field Mesozoic transpressional reactivation. The hypogene sulphides such as pyrite, chalcopyrite, bornite, galena and sphalerite occur in dolomite veins related to the brittle stages 5 and 6.

In the Shangoluwe North and Central deposits, an important fault with profound striae and corrugations affecting the Kanianga Formation (Ku 1.3) displays a normal-sinistral slip movement. In the same formation, a reverse fault and a dip slip normal fault with profound striae and corrugations related to the brittle stage 5 was also identified (Kipata, 2013). The variety of bedding plane orientations observed in the Kundelungu rocks and the pseudo-stratification observed in the breccias can be explained by faulting and drag-folding with an axial plane oriented 74/230, which is related to brittle stage 2 (Fig. 9). In the Kundelungu Group, tectonic breccias containing angular clasts (blocks) of sandy dolomitic shales and laminated dolomitic shales were formed by transverse and strike-slip faults. In the Ferruginous and Dolomitic Breccias, the fragments are characterised by a high aspect ratio of up to 9 (cf. quantitative analysis of the breccias). Copper minerals along the faults include chalcopyrite, bornite, chalcocite, covellite, chrysocolla, shattukite, azurite and malachite associated with minor amounts of galena and sphalerite.

In the Shangoluwe South deposit (site Kat 17 of Kipata et al., 2013), cross-cutting relationships suggest a fracturing event with subvertical fracture planes (Fig. 8G) and well-marked strike-slip striae (brittle stage 4). The contact between the Ferruginous Breccias and the Kundelungu sequence is faulted, and characterised by a sigmoidal gouge. This fault affects both the Mongwe Formation and the Dolomitic and Ferruginous Breccias (Fig. 8E and F). Azurite, chrysocolla, covellite and malachite occur in fractures (Fig. 8H).

6.2. *Unconformities*

Two angular unconformities were observed at Shangoluwe. The first one is an irregular erosional surface that defines the contact between the Dolomitic and Siliceous Breccias (Fig. 8I). The second separates the subhorizontal Siliceous Breccias from the underlying folded Kundelungu sequences (Fig. 8C). The base of the subhorizontal Siliceous Breccias is formed of a 15-20 cm-thick polylithic uncemented layer, indicating an erosional contact. This contact zone is characterised by a unit containing argillaceous shale and argillaceous sandy shale clasts from the Kundelungu units and dolomite clasts in an unconsolidated argillaceous sandy matrix.

7. Interpretation and discussion

7.1. *Sedimentology and geodynamic context*

The upper part of the Kundelungu Group (Biano Subgroup) consists of arkoses, conglomerates, argillaceous sandstones and pelites at the Biano and Kundelungu Plateaux (Alexandre-Pyre, 1967; François, 1973; Dumont et al., 1997; Batumike et al., 2006, 2007). In the Ngule area (northern part of Tenke-Fungurume), the Biano Subgroup consists of fine- to coarse-grained arkoses with intercalated argillaceous sandstones at the base, overlain by a 10 m-thick conglomerate (François, 1973). This conglomerate is made up of clasts of quartzite (60 vol %), sandstone, shale and siliceous dolomite (10 vol %) in a red to white sandy matrix (30 vol %) which

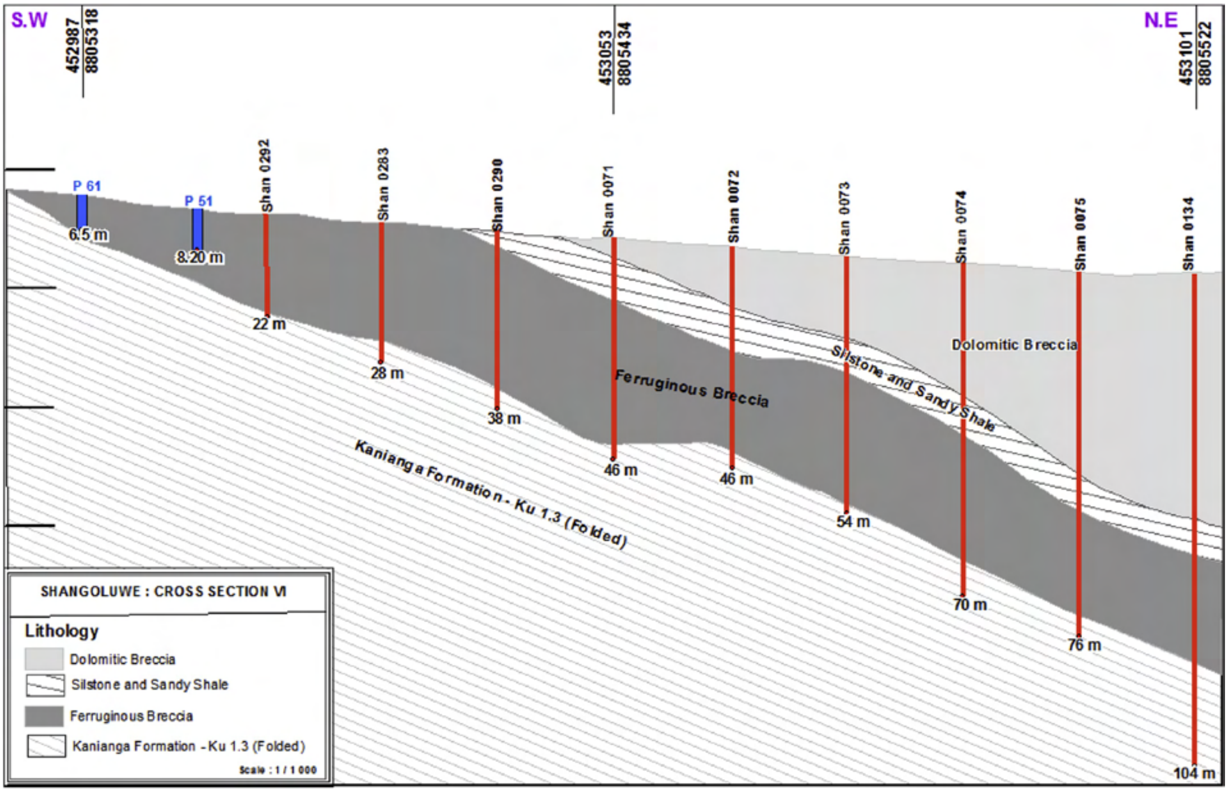

Fig. 6. Shangoluwe cross section VI (Shangoluwe North deposit): Geological interpretation from Schuiling (1940), Cailteux and Dessart (1984) and modified by the results of this study.

consists of coarse grained quartz. In others places (e.g. north and east of Kansenya), this succession is absent and no erosional structure is found. Only brown to grey mauve stratified sandy shale and reddish brown laminated argillaceous shale are present. Sometimes these rocks are overlain by yellow to brownish Cenozoic Kalahari sands (Alexandre, 2002; François, 1973, 2006).

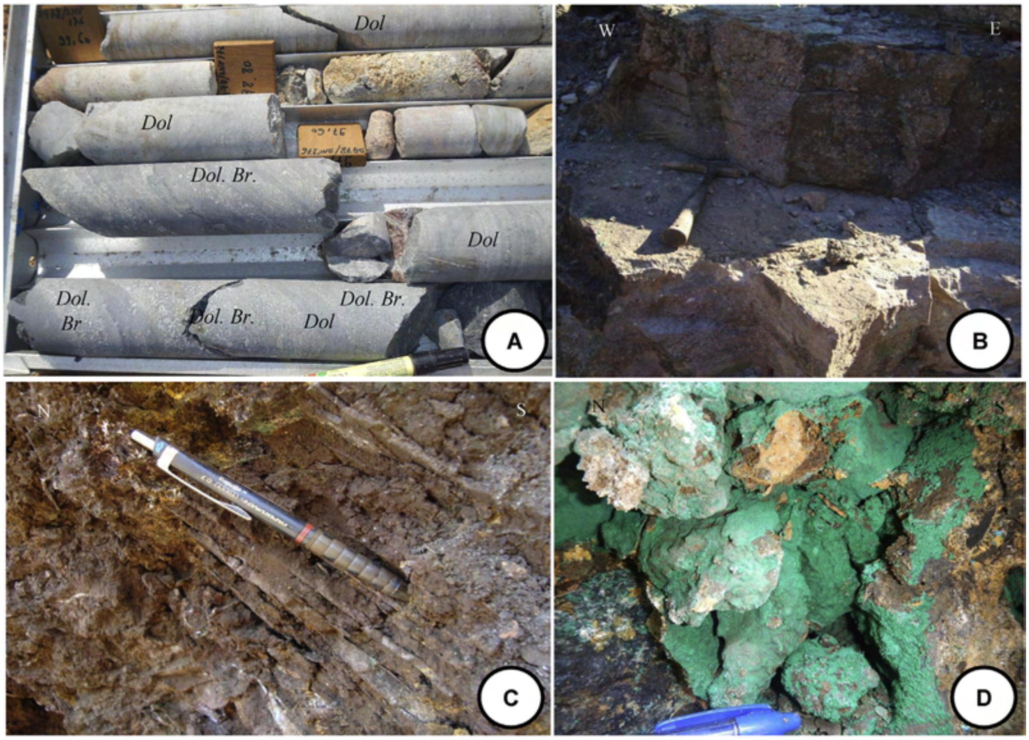

Fig. 7. Turbidity current and macroscopic characteristic of the sedimentary breccias. A: Intercalated layers of stratified and massive dolomite in the Dolomitic Breccias; B: Pseudo-stratification in the Dolomitic Breccias, C: Laminated matrix in the Siliceous Breccias, D: Uncemented breccias bearing supergene mineralisation (Siliceous Breccias).

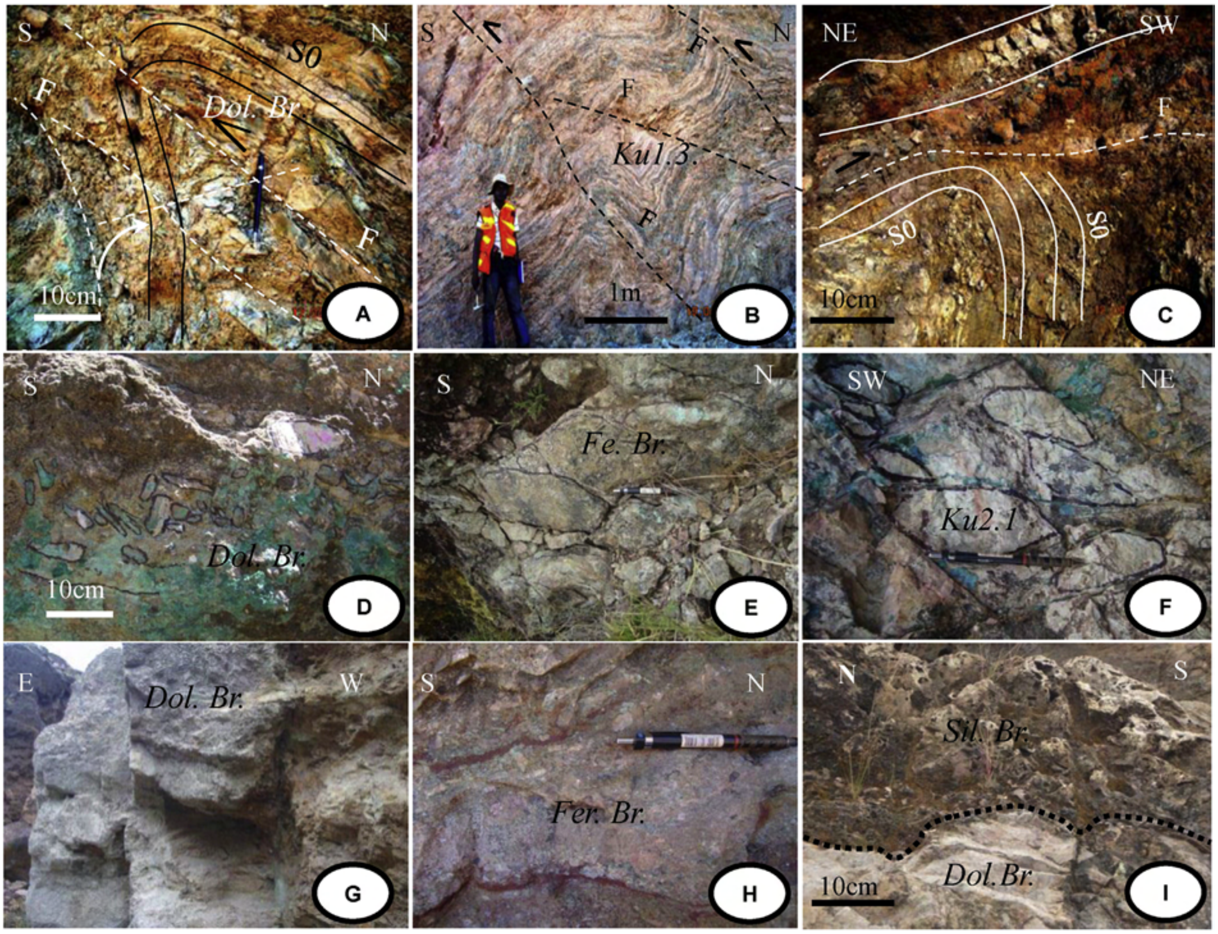

Fig. 8. Faulting, folding and unconformities. A: Back folds (Ku 1.3), B: Drag folds (Ku 1.3), C: Angular unconformity (Ku 1.3), D: Drag folds (Dol.Br.), E and F: Sigmoid in Ferruginous Breccias and Mongwe Formation (Ku 2.1), G: Major fault in the Dolomitic Breccias cross-cutting fragments which are characterised by the high aspect ratio, H: Supergene minerals in fractures in the Ferruginous Breccias, I) Erosional unconformity.

The conglomerate observed in the upper part of the Biano Subgroup is different from the Shangoluwe breccias. Previously, François (2006) and Cailteux and Dessart (1984) interpreted the Shangoluwe breccias as tectonic breccias made up of dolomite fragments from both the Dipeta and Mine Subgroups. Wendorff (2003, 2011) described the same breccias as a syn-tectonic conglomerate within an olistostrome deposited in the Fungurume foreland, implying that these breccias are younger than the Kundelungu Group. The results from this study do not support these interpretations.

The Shangoluwe breccias are characterised by breccias fragments generally weathered into a clayey rock. The clasts are angular to subangular (Fig. 4), indicating a short distance of transportation. They are also characterised by a log normal distribution. The normal and inverse graded bedding indicate a grain and debris flow deposit, including mud flow. Pseudo-stratification, a finely laminated matrix and intercalated layers of siltstone, dolomite and sandy shale indicate deposition through turbidity currents (Fig. 7A–C). The Shangoluwe breccias have therefore a sedimentary origin, but with clasts produced locally from surrounding rocks, i.e. dominantly from the Roan Group and less from the Kundelungu Group. The breccias were sequentially deposited and consist of three different parts (Ferruginous, Dolomitic and Siliceous Breccias).

The mud flow at the base of the Ferruginous Breccias consists of small fragments of dolomite (<1 mm diameter) which has been weathered into a clayey rock. The breccias overlying this layer have larger fragments, up to 50 cm in diameter. The continuity in sedimentation is observed in the northern and southern part of Shangoluwe. It consists of an alternation of breccias made up of small fragments (<1 cm diameter) and white to yellowish or brownish argillaceous shales (2–10 cm thick). In this context, the sedimentary Ferruginous and Dolomitic Breccias are totally different from the tectonic breccias found along the fault zones at Shangoluwe as in the Lufilian arc, and described by several authors such as Okitaudji (1992), Cailteux and Kampunzu (1995), Cailteux et al. (2005a), Kipata et al. (2013), Taylor et al. (2013) and Zientek et al. (2014). These two sedimentary breccias are coeval with the Kanianga and Mongwe formations. The timing of deposition is constrained on the basis of structural and sedimentological evidences:

(i) the breccias were deposited as lenses in both the Kanianga and Mongwe formations and were affected by the same style of deformation, which is related to the Lufilian orogeny (D1 - Kolwezian and D2 – Monwezian phases of Kampunzu and Cailteux, 1999, Figs. 8 and 9, Table 2) and late- to post-Lufilian orogeny events (e.g. brittle stages 4, 5 and 6 of Kipata et al., 2013).

(ii) there is evidence of a continuity of sedimentation through the Ferruginous Breccias and Kanianga Formation, deposition of siltstone and sandy shale beds interlayered within the

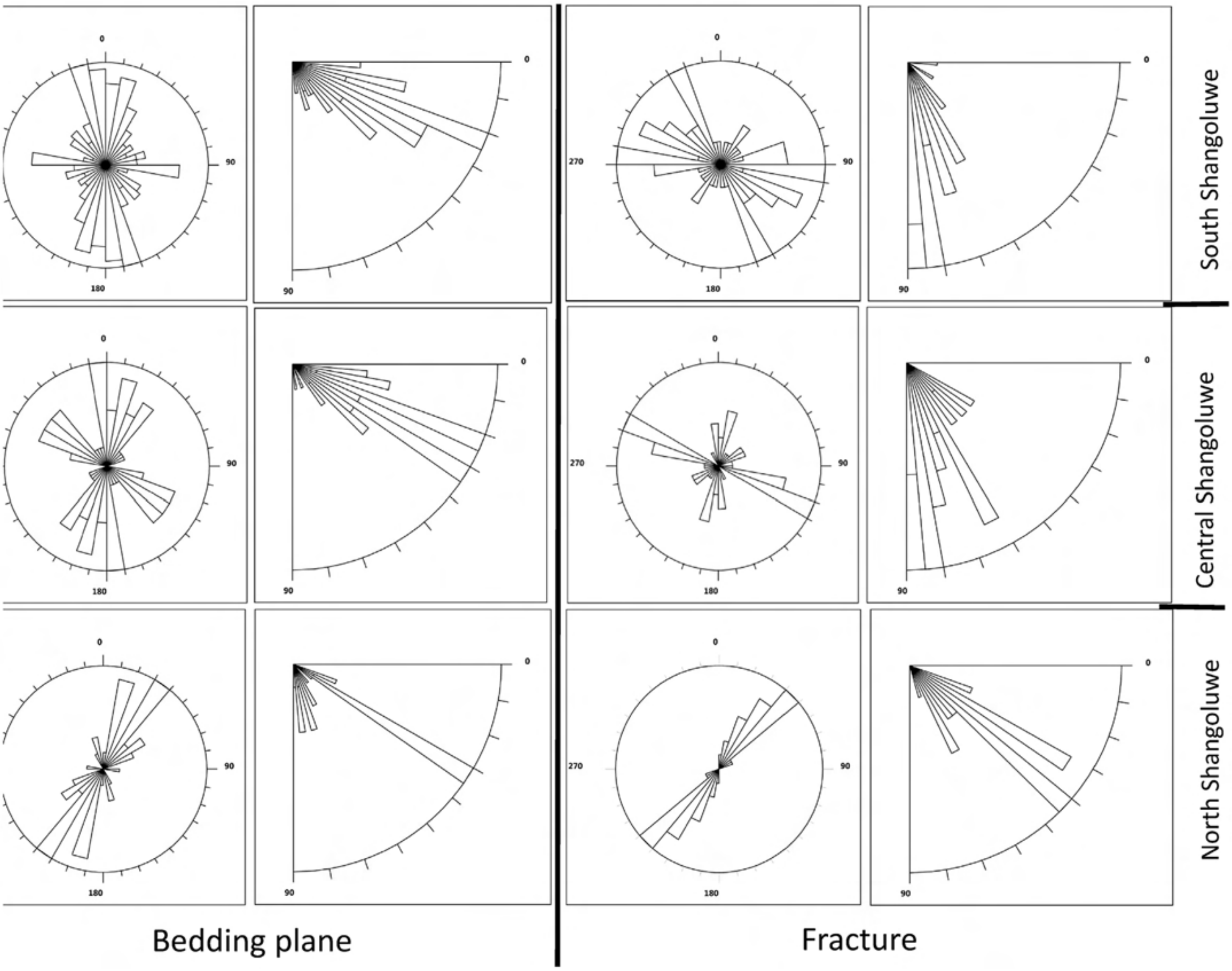

Fig. 9. Bedding plane and fractures in Shangoluwe North, Central and South.

breccia and between the Ferruginous and Dolomitic Breccia (Fig. 6; Table 3; e.g. Schuiling, 1940; Cailteux and Dessart, 1984), and the presence of dolomite, dolomitic shale and shale layers interbedded in these breccias (Figs. 6 and 7A).

The Siliceous Breccias has been deposited through an angular unconformity on both the Kanianga (Ku 1.3) and the Mongwe formations (Ku 2.1) and through an erosional unconformity on top of the Dolomitic Breccias (Fig. 8C and I; Table 3). The Siliceous Breccias is characterised by a recrystallised massive siliceous matrix, but locally laminated at the base. It is overlain by a layer with a coarse-grained matrix and followed by clast-supported breccias. The Siliceous Breccias post-dates the Lufilian orogeny and is possibly younger than the sandstone, conglomerate and pellite of the Biano Subgroup. This hypothesis is supported by the following features:

(i) the upper part of the Siliceous Breccias is characterised by an un-cemented breccias and by the absence of a fine-grained matrix; indicating the termination of a depositional cycle;
(ii) the breccias has not been affected by the Lufilian orogeny as observed on both Ferruginous and Dolomitic Breccias (Kipata, 2013);
(iii) there is an angular unconformity between the Siliceous Breccias and the Kundelungu sequences (Fig. 9C), while the two lower units (Ferruginous and Dolomitic Breccias) are concordant with the Kundelungu rocks (Kanianga, Ku1.3 and Mongwe, Ku 2.1 formations). There is also an erosional unconformity (Fig. 8I) on top of the Dolomitic Breccias that developed prior to deposition of the Siliceous Breccias (Fig. 8I; Table 3). These local unconformities obviously post-date the Lufilian orogeny and are not related to the regional tectonic unconformity defined by El Desouky et al. (2008a) in the foreland, which corresponds to the orogenic paroxysm (Kipata et al., 2013). This regional unconformity is equivalent to the tectonic unconformity observed along the transition zone between the Lufilian arc (Kiubo Formation- Ku 2.2 and Sampwe Formation - Ku 2.3) and the Katanga foreland (the Biano Plateau) in the northern part of the Tenke-Fungurume district.

7.2. Lithostratigraphic position of the Shangoluwe breccias

Wendorff (2003, 2005b) described the breccias at Mufulira and

Table 3
Stratigraphic succession defined at Shangoluwe North and Central according to the result of this study.

Formations	Sedimentological characteristics	Deformation	Cu minerals	Geodynamic context
Siliceous Breccias ~25–50 m thick **Top**	Laminated and massive matrix; short transport of dolomite clasts, immature rock, very to poorly sorted, angular to very angular. Clasts are oriented following the sense of flow. On subsurface the fragmant still uncemented; Evidence of grain flow.	Post-Lufilian orogeny.	Chalcocite, bornite, chalcopyrite, malachite and chrysocolla.	Post-orogenic
Stratigraphy markers: (1) **Erosional unconformity on Dolomitic Breccia: b**etween Dolomitic Breccia and Siliceous Breccia. (2) **Angular unconformity on Kundelungu: b**etween Kundelungu Group (Ku 1.2- Kanianga Formation and Ku2.1 – Mongwe Formation) and Siliceous Breccia.				
Dolomitic Breccias ~50 m thick **Middle**	Pseudo-stratification, short transport of dolomite fragment, graded bedding, immature rock, dissolution, poorly sorted, angular to very angular. In-situ fragmentation. Intercalated layers of sandy dolomitic shale, shale, dolomite and dolomitic shale.	D1 & D2 Lufilian phases.	Chalcocite, chalcopyrite, covelline, bornite, azurite, natif Cu and malachite.	Syn-orogenic and coeval to the deposition of Ku1.3
Conformity: Sandy shale and siltstone layers (~10m thick) like the Kundelungu rocks.				
Ferruginous Breccias ~60 m thick **Bottom**	Pseudo-stratification, intercalation of sandy and argillaceous shale, dissolution, short transport of dolomite fragment. Poorly sorted, angular to very angular. In-situ fragmentation	D1 & D2 Lufilian phases.	Chalcocite, chalcopyrite bornite, azurite malachite, covelline, natif Cu and chrysocolla.	Syn-orogenic and coeval to the deposition of Ku1.3
Mud flow ~3 m thick	Massive red argillaceous matrix within minor fragment of dolomite.	D1 & D2 Lufilian phases.	Chalcocite, chalcopyrite, bornite, azurite malachite, shattukite, chrysocolla.	Syn-orogenic and coeval to the deposition of Ku1.3.
Conformity and continuity of sedimentation (~ 2 m thick): Alternation of white to yellowish or brownish argillaceous shale (2–10 cm of thick) and minor breccia made up of centimeter to millimeter fragments of dolomite in an argillaceous matrix.				
Kanianga Formation (Ku1.3)	Sandy dolomitic shale, dolomitic shale and stratified dolomite	D1 & D2 Lufilian phases.	Chalcocite, bornite, azurite malachite, shattukite Chrysocolla	Syn-orogenic

Mwambishi in the Zambia Copperbelt and interpreted them as synrift clastic deposits (olistostromes) in the Mwashya-Nguba basin. Previously, a tectonic origin was considered for these breccias (Cailteux et al., 1994). Wendorff (2005a) redefined the lithostratigraphy of the Katanga Supergroup as a succession of the Roan, Nguba, Kundelungu, Fungurume and Plateau groups. According to this author, the Fungurume Group is subdivided into the Kambove Formation consisting of olistostromes, the Mutoshi Formation characterised by continental red beds and marginal marine siliciclastics and the Dipeta Formation composed of mixed marginal marine clastic rocks. In the Congo Copperbelt, Wendorff (2000a,b; 2003) considered also the tectonic megabreccias (e.g. Roan Group) including the Shangoluwe breccias as having a sedimentary origin (e.g. olistrostomes), but these breccias were considered as forming the Fungurume Group, younger than the Kundelungu Group. The Shangoluwe breccias was described initially as tectonic breccias consisting essentially of the clasts from the Roan Group (Cailteux and Dessart, 1984; François, 2006). However, our observations at Shangoluwe indicate that the Shangoluwe breccias are not a single sedimentary unit (Wendorff, 2011) or a tectonic breccias (Cailteux and Dessart, 1984; François, 2006), but three distinct layers can be distinguished among these breccias including Ferruginous, Dolomitic and Siliceous Breccias (Fig. 6, Table 3). These breccias contain Cu mineralisation associated with minor Zn-Pb mineralisation. The Shangoluwe breccias are interpreted as having a sedimentary origin and were deposited as lenses by gravity flow.

Based on the results from this study, it is proposed to include the three breccias defined at Shangoluwe into the lithostratigraphy of the Katanga Supergroup as defined by Batumike et al. (2007). The lenses of Ferruginous and the Dolomitic Breccias are contemporaneous with the Kanianga (Ku 1.3) and Mongwe (Ku 2.1) formations while the Siliceous Breccias constitute an additional unit of the Biano Subgroup (Table 3).

7.3. Timing of copper mineralisation

Several metallogenic models have been proposed for the origin of copper and cobalt mineralisation in the Copperbelt including syngenetic (Garlick, 1961; Fleischer et al., 1976), diagenetic (Cailteux et al., 2005b; Muchez et al., 2015) and syn-orogenic (McGowan et al., 2003, 2006) models. In addition, El Desouky et al. (2008a) proposed a post-orogenic fluid–mixing model for the stratiform mineralisation in the Lufilian foreland controlled by strike-slip faults. El Desouky et al. (2009, 2010) distinguished two main hypogene Cu-Co sulphide phases in the Congo Copperbelt: an early stratiform emplacement by hydrothermal fluids and a late diagenetic to syn-orogenic hypogene Cu-Co mineralisation. The hypogene minerals are often replaced by supergene sulphides while the supergene Cu-Co oxide minerals are mainly concentrated along cracks and in fracture zones associated with faults. This clearly indicates the role of tectonic structures and alteration processes in leaching, remobilising and upgrading the primary mineralisation (Chavez, 2000; Torremans et al., 2013). Similar secondary enrichments induced by the Lufilian folding and faulting are observed in different deposits inside the Lufilian arc (Haest and Muchez, 2011; Van Langendonck et al., 2013; Kipata et al., 2013). Faults and veins contain hypogene sulphides (pyrite, chalcopyrite, bornite, galena and sphalerite) and younger supergene minerals such as azurite, chrysocolla, chalcocite, covellite and malachite.

The Shangoluwe breccias were affected by in-situ fragmentation during the Lufilian orogeny and dissolution of dolomitic fragments, which allowed fluid circulation. However, the emplacement of Cu mineralisation in veins (e.g. in the breccias and the surrounding Kundelungu rocks) and in the matrix of the sedimentary breccias (Ferruginous and Dolomitic Breccias) took place during late stages of the Lufilian orogeny or after this orogeny. The mineralisation could be associated with the brittle stage 5 (Lufilian arc parallel extension) and stage 6 (post-orogenic extension) of Kipata et al. (2013). The supergene minerals associated with the hypogene sulphides (pyrite, bornite, chalcopyrite) occur in the younger Siliceous Breccias and are related to late Cenozoic remobilisation of the mineralisation in fractures, pores and cavities created by the dissolution of dolomite fragments (De Putter et al., 2010). Although there are euhedral pyrite crystals disseminated in the dolomite clasts, an early diagenetic Cu sulphide phase has not been recognised at Shangoluwe.

8. Conclusion

The Shangoluwe breccias were defined on the basis of the nature of the matrix and clasts. Three types of breccias were identified at Shangoluwe, from bottom to top: Ferruginous, Dolomitic and Siliceous Breccias. This relationship is based on the presence of interbedded layers, erosional surfaces and angular unconformities. The study of these breccias has indicated that:

(1) The Shangoluwe breccias have a sedimentary origin and are constituted by dolomite clasts from rocks of the Katanga Supergroup (Roan and Kundelungu groups).
(2) The quantitative analysis of the Ferruginous and Dolomitic breccias indicates a short distance of transport, deposition of breccias by gravity flow (log normal distribution of fragment) and a later in-situ fragmentation of large clasts during the Lufilian orogeny (high aspect ratio). The short distance of transport is also supported by the immaturity, low sphericity and poor sorting of the clasts.
(3) The breccias were deposited by gravity flow as shown by the presence of mud flow at the base of the Ferruginous Breccias, debris flow (in the Ferruginous Breccias, Dolomitic Breccias and base of Siliceous Breccias) and grain flow at the top of Siliceous Breccias.
(4) The turbidity currents are marked by the presence of a finely laminated matrix in the Siliceous Breccias, and graded bedding and pseudo-stratifications in the Ferruginous and Dolomitic Breccias with layers of sandy shale, dolomitic shale, shale and dolomite. They have the same petrographic characteristics as the Kundelungu rocks (Kanianga and Mongwe formations).
(5) The stratigraphic and sedimentological observations indicate that the deposition of the Ferruginous and Dolomitic Breccias is coeval to the deposition of the Kanianga Formation (Ku 1.3) and the Mongwe Formation (Ku 2.1).
(6) The structural data indicate that the Siliceous Breccias postdates the Lufilian orogeny, but the Ferruginous and Dolomitic Breccias and surrounding Kundelungu rocks were affected by the Lufilian orogeny. The Siliceous Breccias may have been deposited during the early Palaeozoic as the Biano Subgroup. The Ferruginous and Dolomitic Breccias are part of the Kanianga and Mongwe formations, and the Siliceous Breccias are attributed to the Biano Subgroup (Table 3).
(7) The Cu sulphides associated with minor Pb-Zn sulphides in the Ferruginous and Dolomitic Breccias precipitated during deformation stage 5 (Lufilian arc parallel extension) and stage 6 (post-orogenic extension) of Kipata et al. (2013). The voids between clasts, karstic dissolution on dolomite fragments and fracturating allowed mineralising fluid circulation.

Acknowledgements

This results presented in this paper are part of a M.Sc. thesis by P. Mambwe at the University of Lubumbashi (DRC). Part of the thesis has been carried out at the KU Leuven (Belgium). Field assistance was provided through project RA_S1_RDC_GEODYN of the Belgian Cooperation to D. Delvaux. The authors would like to thank Mr. Alphonse Kaputo, Director of the Geological Department of Gécamines S.A., for allowing access to the concession. Gracie Tambwe and Eric Tshisola are thanked for their field assistance. Sebastien Lavoie, Budi Santoso, Robert North, dr. Isabelle Fay and Joseph Nzita are thanked for their encouragement and documentation. dr. Jean Liégeois and dr. Thierry De Putter are thanked for their constructive remarks on an earlier version of the manuscript. Finally, the chief editor (Read Brown Mthanganyika Mapeo), dr. Jacques Batumike, dr Jacques Cailteux and an anonymous Reviewer are gratefully acknowledged for their remarks and suggestions.

References

Alexandre, J., 2002. Les cuirasses latéritiques et autres formations ferrugineuses tropicales. Exemple du Haut Katanga méridional. Musée Royal de l'Afrique Centrale, Tervuren, Belgique, série in-8. Ann. Des. Sci. Géologiques 107, 118.
Alexandre-Pyre, S., 1967. Les processus d'aplanissement de piémont dans les régions marginales du plateau des Biano. Publications de l'Université Officielle du Congo, Lubumbashi, pp. 3–50.
Armstrong, R.A., Master, S., Robb, L.J., 2005. Geochronology of the Nchanga Granite, and constraints on the maximum age of the Katanga Supergroup, Zambian Copperbelt. J. Afr. Earth Sci. 42, 32–40.
Batumike, J.M., Kampunzu, A.B., Cailteux, J.H., 2006. Petrology and geochemistry of the Neoproterozoic and Nguba Kundelungu Groups, Katanga Supergroup, southeast Congo: Implications for provenance and geotectonic setting paleo-weathering. J. Afr. Earth Sci. 44, 97–115.
Batumike, M.J., Kampunzu, A.B., Cailteux, J.H., 2007. Lithostratigraphy, basin development, base metal deposits, and regional correlations of the Neoproterozoic Nguba and Kundelungu rock successions, Central African Copperbelt. Gondwana Res. 11, 432–447.
Bérubé, D., Jébrak, M., 1999. High precision boundary fractal analysis for shape characterization. Comput. Geosci. 5, 1059–1071.
Binda, P.L., Mulgrew, J.R., 1974. Stratigraphy of the Copper Occurrences in the Zambian Copperbelt. Centenaire de la société géologique de Belgique. Gisements stratiformes et provinces cuprifères, Liège, pp. 215–233.
Binda, P.L., Porada, H., 1995. Observations on the Katangan breccias of Zambia. Musée Royal de l'Afrique Centrale, Tervuren, Belgium. Ann. Sci. Géol. Belg. 101, 49–62.
Cailteux, J., Dessart, A., 1984. L'ancienne exploitation de Shangulowe : Synthèse géologique et minière. Rapport N° GEO/Rapport Annuel 909 du Département Géologique, Gécamines, Likasi, Unpublished, p. 18.
Cailteux, J., 1994. Lithostratigraphy of the Neoproterozoic Shaba-type (Zaïre) Roan Supergroup and metallogenesis of associated stratiform mineralization. J. Afr. Earth Sci. 19, 279–301.
Cailteux, J., Binda, P.L., Katekesha, W.M., Kampunzu, A.B., Intiomale, M.M., Kapenda, D., Kaunda, C., Ngongo, K., Tshiauka, T., Wendorff, M., 1994. Lithostratigraphical correlation of the Neoproterozoic Roan Supergroup from Shaba (Zaïre) and Zambia in the central African copper-cobalt metallogenic province. J. Afr. Earth Sci. 19, 265–278.
Cailteux, J.L.H., Kampunzu, A.B., 1995. The Katangan tectonic breccias in the Shaba Province (Zaire) and their genetic significance. Ann. Sci. Géol. R. Mus. Central Afr. 101, 63–76.
Cailteux, J.L.H., Kampunzu, A.B., Batumike, M.J., 2005a. Lithostratigraphic position and petrographic characteristics of R.A.T (Roches Argilo-Talqueuses) Subgroup, Neoproterozoic Katanga belt (Congo). J. Afr. Earth Sci. 42, 82–94.
Cailteux, J.L.H., Kampunzu, A.B., Lerouge, C., Kaputo, A.K., Milesi, J.P., 2005b. Genesis of sediment-hosted stratiform copper-cobalt deposits, Central African Copperbelt. J. Afr. Earth Sci. 42, 134–158.
Cailteux, J., Kampunzu, A.B., Lerouge, 2007. Characterization and revision of the Neoproterozoic Mwashya subgroup lithostratigraphy in the Central African Copperbelt, Mwashya-hosted base metal deposits and regional correlations. Gondwana Res. 11, 392–409.
Cailteux, J., Misi, A.J.H., 2007. Neoproterozoic sediment-hosted base metal deposits of Western Gondwana. Gondwana Res. 11, 344–345.
Chabu, M., Boulègue, J., 1992. Barian feldspar and muscovite from the Kipushi Zn-Pb-Cu deposit, Shaba Zaïre. Can. Mineral. 30, 1143–1152.
Chabu, M., 1995. The geochemistry of phlogopite and chlorite from the Kipushi Zn-Pb-Cu deposit, Shaba, Zaire. Can. Mineral. 33, 547–558.
Chavez, W.X.J., 2000. Supergene oxidation of copper deposit: Zonation and distribution of copper oxide minerals. Soc. Econ. Geol. Newsl. 41, 9–21.
Cojan, I., Renard, M., 2006. Sédimentologie, second ed., p. 440 Dunod.
De Magnée, I., François, A., 1988. The origin of the Kipushi (Cu, Zn, Pb) deposits in direct relation with a Proterozoic salt diapir. Copperbelt of Central Africa, Shaba, Republic of Zaïre. In: Friedrich, G.H., Herzig, P.M. (Eds.), Base Metal Sulfide Deposits. Berlin Heidelberg, Springer-Verlag, pp. 74–93.
De Putter, T., Mees, F., Decrée, S., Dewaele, S., 2010. Malachite, an indicator of major Pliocene Cu remobilization in a Karstic environment (Katanga, Democratic Republic of Congo). Ore Geol. Rev. 38, 90–100.
De Waele, B., Johnson, S.P., Pisarevsky, S.A., 2008. Palaeoproterozoic to Neoproterozoic growth and evolution of the eastern Congo Craton: Its role in the Rodinia puzzle. Precambrian Res. 160, 127–141.
Dumont, P., Hanon, M., Ngoyi, L.K., 1997. La structure géologique du Plateau des Biano. Musée Royal de l'Afrique Centrale, Tervuren. Rappel Annales 1995-1996, pp. 169–182.
El Desouky, H.A., Muchez, Ph, Dewaele, S., Boutwood, S.A., Tyler, R., 2007. The stratiform copper mineralization of the Lufukwe anticline, Lufilian foreland, Democratic Republic Congo. Geol. Belg. 10, 148–151.
El Desouky, H., Muchez, Ph, Boutwood, A., Tyler, R., 2008a. Postorogenic origin of the stratiform Cu mineralization at Lufukwe, Lufilian Foreland, Democratic Republic of Congo. Econ. Geol. 103, 555–582.
El Desouky, H.A., Muchez, Ph, Tyler, R., 2008b. The sandstone-hosted stratiform copper mineralisation at Mwitapile and its relation to the mineralisation at Lufukwe, Lufilian foreland, Democratic Republic Congo. Ore Geol. Rev. 34, 561–579.
El Desouky, H.A., Muchez, Ph, Cailteux, J., 2009. Two Cu-Co sulfide phases and

contrasting fluid systems in the Katanga Copperbelt, Democratic Republic of Congo. Ore Geol. Rev. 36, 315–332.

El Desouky, H.A., Muchez, Ph, Boyce, A.J., Schneider, J., Cailteux, J.L.H., Dewaele, S., von Quadt, A., 2010. Genesis of sediment-hosted stratiform copper-cobalt mineralization at Luiswishi and Kamoto, Katanga Copperbelt (Democratic Republic of Congo). Miner. Deposita 45, 735–763.

François, A., 1973. L'extrémité occidentale de l'arc cuprifère Shabien. Etude géologique. Mémoire du Département Géologique, Gécamines, Likasi (République du Zaïre), p. 65.

François, A., 1974. Stratigraphie, tectonique et minéralisation dans l'arc cuprifère du Shaba. In: Bartholomé, P. (Ed.), Gisements Stratiformes et Provinces Cuprifères. Centenaire de la Société Géologique de Belgique, Liège, pp. 79–101.

François, A., 2006. La partie centrale de l'Arc cuprifère du Katanga. Tervuren (Belgique). Afr. Geosci. Collect. 109, 70.

Fleischer, V.D., Garlick, W.G., Haldane, R., 1976. Geology of the Zambian Copperbelt. In: Wolf, K.H. (Ed.), Handbook of Stratabound and Stratiform Ore Deposits. Elsevier, New York 6, pp. 223–352.

Garlick, W.G., 1961. The syngenetic theory. In: Mendelsohn, F. (Ed.), The Geology of the Northern Rhodesian Copperbelt. McDonald, London, pp. 146–165.

Grantham, G.H., Maboko, M., Eglington, B.M., 2003. A review of the evolution of the Mozambique belt and implications for the amalgamation and dispersal of Rodinia and Gondwana. Geol. Soc. Lond. Special Publ. 206, 401–425.

Grujenschi, C., 1978. Quelques observations sur la position stratigraphique de la série des mines au Shaba. Ann. la Soc. Géol. Belg. 101, 1–11.

Hanson, R.E., Wardlaw, M.S., Wilson, T.J., Mwale, G., 1993. U-Pb zircon ages from the Hook granite massif and Mwembeshi dislocation: constraints on Pan-African deformation, plutonism, and transcurrent shearing in central Zambia. Precambrian Res. 63, 189–209.

Haest, M., Muchez, Ph, Dewaele, S., 2007. Metallogenesis of the Dikulushi Cu-Ag ore deposit in the Lufilian foreland (Democratic Republic of the Congo). Geol. Belg. 10, 152–155.

Haest, M., Muchez, Ph, 2011. Stratiform and vein-type deposits in the Pan-African Orogen in Central and Southern Africa: Evidence for multiphase mineralization. Geol. Belg. 14, 23–44.

Hitzman, M.W., Selley, D., Bull, S., 2010. Formation of sedimentary rock-hosted stratiform copper deposits through earth history. Econ. Geol. 105, 627–639.

Hitzman, M.W., Broughton, D., Selley, D., Woodhead, J., Wood, D., Bull, S., 2012. The Central African Copperbelt: diverse stratigraphic, structural and temporal settings in the world's largest sedimentary copper district. Soc. Econ. Geol. Spec. Publ. 16, 487–514.

Jackson, M.P.A., Warin, O.N., Woad, G.M., Hudec, M.R., 2003. Neoproterozoic allochthonous salt tectonics during the Lufilian orogeny in the Katangan Copperbelt, central Africa. Geol. Soc. Am. Bull. 115, 314–330.

Jébrak, M., 1997. Hydrothermal breccia in vein-type ore deposits: a review of the mechanisms, morphology and size distribution. Ore Geol. Rev. 12, 111–134.

Kamona, A.F., Lévêque, J., Friedrich, G., Haack, U., 1999. Lead isotopes of the carbonate-hosted Kabwe, Tsumeb, and Kipushi Pb–Zn–Cu sulphide deposits in relation to Pan-African orogenesis in the Damaran–Lufilian fold belt of central Africa. Miner. Deposita 34, 273–283.

Kampunzu, A.B., Cailteux, J., 1999. Tectonic evolution of the Lufilian Arc (Central African Copperbelt) during Neoproterozoic Pan-African orogenesis. Gondwana Res. 2, 401–421.

Kampunzu, A.B., Cailteux, J.H., Kamona, A.F., Intiomale, M.M., Melcher, F., 2009. Sediment-hosted Zn-Pb-Cu deposit in the Central African Copperbelt. Ore Geol. Rev. 35, 263–297.

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

Kipata, M.L., 2013. Brittle Tectonics in the Lufilian Fold-and-thrust Belt and its Foreland. An insight into the stress field record in relation to moving plates (Katanga, DRC). PhD thesis, K.U. Leuven, Belgium, p. 182.

Kipata, M.L., Delvaux, D., Sebagenzi, M.N., Cailteux, J., Sintubin, M., 2013. Brittle and stress field evolution in the Pan-African Lufilian and its foreland (Katanga, DRC): from orogenic compression to extensional collapse, transpressional inversion and transition to rifting. Geol. Belg. 16, 1–17.

Lorilleux, G., Cuney, M., Jébrak, M., Rippert, J.C., Portella, P., 2003. Chemical brecciation processes in the Sue unconformity-type deposit. J. Geochem. Explor. 80, 241–258.

Lowe, D.R., 1979. Sediment gravity flows: their classification and some problems of application to natural flows and deposits. In: Doyle, L.J., Pilkey, O.H. (Eds.), Geology of Continental Slopes, Special Publication of the Society of Economic Paleontologists and Mineralogists, vol. 27, pp. 75–82.

Mambwe, P., Milan, L., Batumike, J., Lavoie, S., Jébrak, M., Kipata, L., Chabu, M., Mulongo, S., Lubala, R.T., Delvaux, D., Muchez, Ph, 2017. Lithology, petrography and Cu mineralisation of the Neoproterozoic glacial Mwale Formation at the Shanika syncline (Tenke Fungurume, Congo Copperbelt; Democratic Republic of Congo). J. Afr. Earth Sci. 129, 898–909.

Master, S., Rainaud, C., Armstrong, R.A., Phillips, D., Robb, L.J., 2005. Provenance ages of the Neoproterozoic Katanga Super group (African Central, Copperbelt) with implication for basin evolution. Megabreccia from Mufulira, Copperbelt of Zambia. J. Afr. Earth Sci. 42, 61–81.

McGowan, R., Roberts, S., Foster, Boyce, A.J., Coller, D., 2003. Origin of copper-cobalt deposit of the Zambia Copperbelt: an epigenetic view from Nchanga. Geology 31, 494–500.

McGowan, R., Roberts, S., Boyce, A., 2006. Origin of the Nchanga copper-cobalt deposits of the Zambian Copperbelt. Miner. Deposita 40, 617–638.

Morrow, D.W., 1982. Descriptive field classification of sedimentary and diagenetic breccia fabrics in carbonate rocks. Bull. Can. Pet. Geol. 30, 227–229.

Muchez, Ph, André-Mayer, A.S., El Desouky, A.H., Reisberg, L., 2015. Diagenetic origin of the stratiform Cu–Co deposit at Kamoto in the Central African Copperbelt. Miner. Deposita 50, 437–447.

Okitaudji, R.L., 1992. Interprétation sédimentologique du Roan (Précambien supérieur) du Shaba (Zaïre) et place des minéralisations cupro-cobaltifère. J. Afr. Earth Sci. 14, 371–386.

Porada, H., Berhorst, V., 2000. Towards a new understanding of the Neoproterozoic-Early Palaeozoic Lufilian and northern Zambezi Belts in Zambia and the Democratic Republic of Congo. J. Afr. Earth Sci. 30, 727–771.

Schuiling, H., 1940. Shangoluwe Cross Section VI. Département de Géologie, Gécamines, Likasi, p. 10. Unpublished.

Schuh, W., Leveille, R.A., Fay, I., North, R., 2012. Geology of the Tenke-Fungurume sediment-hosted strata-bound copper-cobalt district, Katanga, Democratic Republic of Congo. Soc. Econ. Geol. Special Publ. 16, 269–301.

Taylor, C.D., Causey, J.D., Denning, P.D., Hammarstrom, J.M., Hayes, T.S., Horton, J.D., Kirschbaum, M.J., Parks, H.L., Wilson, A.B., Wintzer, N.E., Zientek, M.L., 2013. Descriptive Models, Grade-tonnage Relations, and Databases for the Assessment of Sediment-hosted Copper Deposits - with Emphasis on Deposits in the Central Africa Copperbelt. Democratic Republic of the Congo and Zambia. U.S. Geological Survey Scientific Investigations Report 2010–5090–J, 154 p. and data files.

Torremans, K., Gauquie, J., Boyce, A.J., Barrie, C.D., Dewaele, S., Sikazwe, O., Muchez, Ph, 2013. Remobilisation features and structural control on ore grade distribution at the Konkola stratiform Cu–Co ore deposit, Zambia. J. Afr. Earth Sci. 79, 10–23.

Van Langendonck, S., Muchez, Ph, Dewaele, S., Kaputo, A.K., Cailteux, J., 2013. Petrographic and mineralogical study of the sediment-hosted Cu-Co ore deposit at Kambove West in the central part of the Katanga Copperbelt (DRC). Geol. Belg. 16, 91–104.

Wendorff, M., 2000a. Genetic aspects of the Katangan megabreccias: Neoproterozoic of Central Africa. J. Afr. Earth Sci. 30, 703–715.

Wendorff, M., 2000b. Revision of the stratigraphical position of the 'Roches Argilo-Talqueuse' (R.A.T) in the Neoproterozoic Katanga belt, south Congo. J. Afr. Earth Sci. 30, 717–726.

Wendorff, M., 2003. Stratigraphy of the Fungurume Group - evolving foreland basin succession in the Lufilian fold-thrust belt, Neoproterozoic-Lower Palaeozoic, Democratic Republic of Congo. S. Afr. J. Geol. 106, 17–34.

Wendorff, M., 2005a. Evolution of Neoproterozoic-Lower Paleozoic Lufilian arc, Central Africa: a new model based on syntectonic conglomerates. J. Geol. Soc. Lond. 162, 5–8.

Wendorff, M., 2005b. Lithostratigraphy of the Neoproterozoic syn-rift sedimentary megabreccia from Mwambishi, Copperbelt of Zambia and correlation with olistostrome succession from Mufulira. South Afr. J. Geol. 108, 505–521.

Wendorff, M., 2011. Tectonosedimentary expressions of the evolution of the Fungurume foreland basin in the Lufilian Arc, Neoproterozoic-Lower Palaeozoic, Central Africa. Geol. Soc. Lond. Spec. Publ. 357, 69–83.

Zientek, M.L., Bliss, J.D., Broughton, D.W., Christie, M., Denning, P.D., Hayes, T.S., Hitzman, W.M., Horton, J.D., Frost-Killian, S., Jack, D.J., Master, S., Parks, H.L., Taylor, C.D., Wilson, A.B., Wintzer, N.E., Woodhead, J., 2014. Sediment-hosted Stratabound Copper Assessment of the Neoproterozoic Roan Group. Central African Copperbelt, Katanga Basin, Democratic Republic of the Congo and Zambia. U.S. Geological Survey Scientific Investigations Report 2010–5090–T, p. 162, and spatial data. http://dx.doi.org/10.3133/sir20105090T.