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Lithostratigraphic and structural controls on sulphide mineralisation at the Kamoa copper deposit, Democratic Republic of Congo

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ABSTRACT

The Kamoa copper deposit, 25 km west of the Kolwezi Cu–Co district in Democratic Republic of Congo, is one of the largest high-grade copper deposits in the world. Kamoa is a recent discovery on the western edge of the Congolese part of the Central African Copperbelt (CACB). Two main rock units are present at Kamoa, sandstone and siltstone of the Mwashya Subgroup (Roan Group), and overlying diamictite and interbedded siltstone-sandstone of the Grand Conglomérat unit (Nguba Group). The deposit is at a redox boundary at the base of the Grand Conglomérat.

Drill-core data indicate that the Kamoa deposit includes areas of higher and lower grade, some of which appear at the deposit-scale to be related to known or inferred faults. In the southern part of the Kamoa deposit, a NNW-trending zone of abrupt change in stratigraphic thickness named the "Mupaka fault" correlates with elevated copper grades. Thickness variations, facies changes, steep bedding, and rotated mesoscopic faults demonstrate that the Mupaka fault is a syn-sedimentary normal fault that was active during deposition of Nguba Group rocks. Similar to syn-depositional and subsequently inverted extensional faults known to localise ore at other CACB deposits, particularly in the Zambian Copperbelt, the Mupaka fault was an important control on mineralisation at Kamoa.

1. Introduction

The recently discovered Kamoa deposit (759 Mt at 2.57 wt% copper), 25 km west of the Kolwezi Cu–Co deposits in Democratic Republic of Congo (DRC; Fig. 1) is located on the western edge of the DRC part of the Central African Copperbelt (CACB; Broughton and Rogers, 2010; Parker et al., 2013; Schmandt et al., 2013; Twite, 2016). Sedimentary rock-hosted stratiform copper deposits of the CACB are hosted by the Neoproterozoic Katanga Supergroup (Fig. 2; François, 1973; Cailteux et al., 2005; Kampunzu et al., 2009; El Desouky et al., 2009; Haest and Muchez, 2011). Most of the known CACB deposits in the DRC are hosted by dolomitic rocks of the Mines Subgroup in the lower part (Roan Group) of the succession (Francois, 1973; Cailteux et al., 2005), whereas Kamoa occurs at the base of a stratigraphically higher diamictite, the Grand Conglomérat or Mwale Formation of the basal Nguba Group (Broughton and Rogers, 2010; Schmandt et al., 2013).

Borehole data indicate that the size of the deposit is at least 10 km by 23 km (Fig. 3). In other DRC stratiform copper deposits, ore bodies typically occur as fragments of the Mines Subgroup within a mega-breccia, where it has been demonstrated in many studies that mineralisation pre-dated brecciation and folding (Cailteux, 1994; Cailteux et al., 2005, 2018; De Waele et al., 2006). In contrast, Kamoa is hosted in an unbrecciated continuous stratigraphic unit above the Roan Group and shares characteristics with some of the Zambian deposits in the CACB (Selley et al., 2005), as well as the Polish Kupferschiefer deposits (Oszczepalski, 1989; Kucha, 2003).

Previous research on Kamoa yielded information about the host stratigraphy and mineralisation of the deposit (Broughton and Rogers, 2010; Parker et al., 2013; Schmandt et al., 2013), but deposit-scale controls on sulphide distribution and grade remain incompletely understood. This paper, which stems from MSc. studies of one of the authors (Twite, 2016), focuses on these controls of the copper ore at Kamoa.

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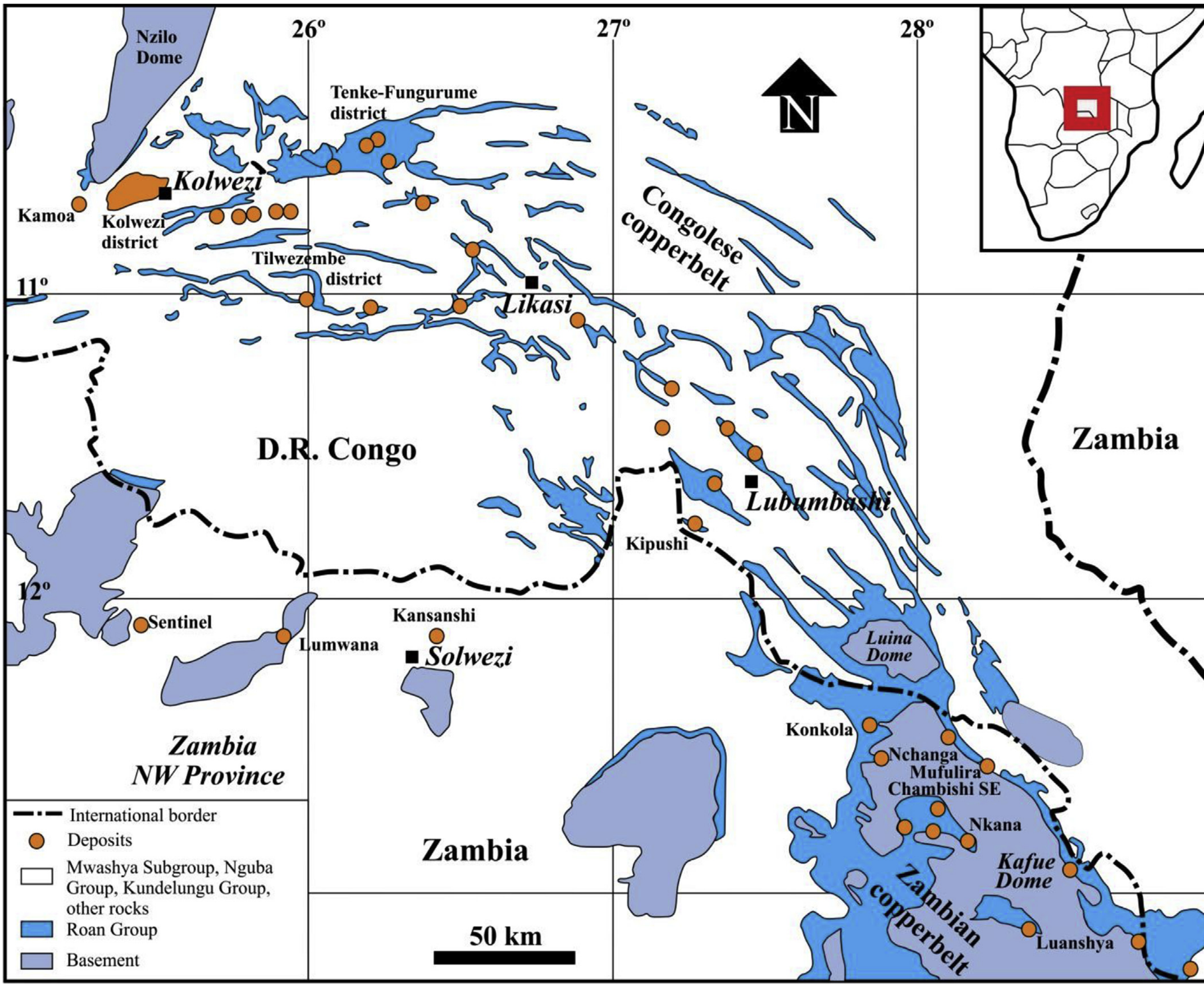

Fig. 1. Simplified geological map of the Central African Copperbelt and Katangan basin showing locations of major deposits and cities; inset map shows the location of the map in southeastern DRC. The Katangan basin consists of an inboard (northeastern; Congolese) and outboard (southwestern; Zambian) region. The Congolese part of the Copperbelt curves from Lubumbashi in the east northwestward to Tenke Fungurume and then west to Kolwezi; this area is characterised by basement-detached, allochthonous deposits of the External Fold-and-Thrust Belt (Lufilian deformation ca. 590-530 Ma). The Kamoa deposit lies on the western edge of the Katangan basin, where the host rocks are relatively undeformed. Modified from François (1973).

2. Regional geology

The Central African Copperbelt (CACB) is the world's largest sedimentary-rock-hosted stratiform copper province. It is hosted in metasedimentary rocks of the Neoproterozoic Katanga Supergroup (Cailteux et al., 2005; Batumike et al., 2007; Cailteux and De Putter, 2018), in the Pan-African Lufilian arc, a regional fold belt located between the Congo craton in the north and the Kalahari craton in the south (Unrug, 1983; Cosi et al., 1992). The northern part of the CACB forms a convex belt encompassing deposits in both the classical Zambian and the DRC Copperbelts. Deposits in the "domes" region of northwestern Zambia have been included in this province (Fig. 1; Selley et al., 2005).

The Katanga Supergroup consists of the Roan, Nguba, and Kundelungu Groups (Cailteux et al., 2005; Batumike et al., 2007). The 883 ± 10 Ma age of the Nchanga Granite provides a maximum age for the start of deposition of the Katanga Supergroup (Armstrong et al., 2005). In summarily, the Supergroup records two periods of rift sedimentation at the beginning of the Roan and uppermost Roan - Nguba times, each followed by more passive phases of subsidence and sedimentation (Hitzman et al., 2012). A thick diamictite, the Grand Conglomérat, marks the onset of Nguba sedimentation. The youngest Kundelungu sequence also began with deposition of a diamictite, the Petit Conglomérat, but evidence for coincident rifting is absent.

The Katangan rocks were affected by the Lufilian orogeny (ca. 590 – 530 Ma) (Fig. 1; Rainaud et al., 2005; Selley et al., 2005) during the collision of the Angola-Kalahari and Congo-Tanzania plates, with accompanying northeast-directed thrusting (Kampunzu and Cailteux, 1999; Porada and Berhorst, 2000). The Lufilian arc comprises a convex-northwards suite of folds and structures (François, 1973; Daly, 1986; Jackson et al., 2003; Kampunzu and Cailteux, 1999; Kipata et al., 2013), traditionally interpreted as reflecting a compressive regime that developed during basin inversion (François, 1973; Kampunzu and Cailteux, 1999; Key et al., 2001; Cailteux et al., 2018). Jackson et al. (2003) proposed that during the Lufilian orogeny, the Katangan basin was transformed first by extrusion of allochthonous evaporites (De Magnée and François, 1988), then by orogenic shortening. Most recently, it has been argued that the fundamental structural architecture and style of the northern part of the Lufilian arc containing the CACB is controlled by salt tectonics with a lesser component of horizontal shortening (Selley et al., 2018).

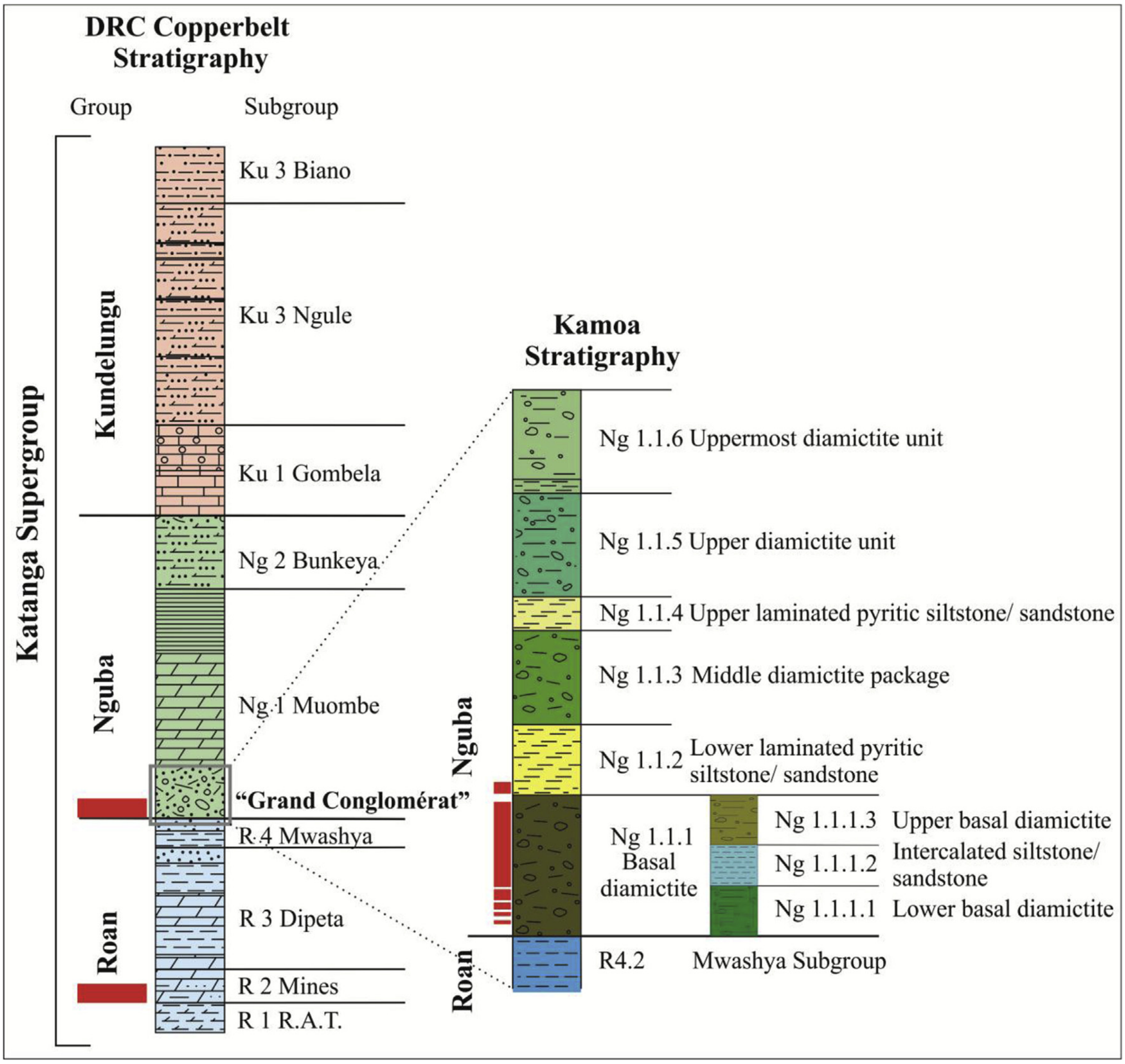

Fig. 2. Generalised stratigraphy of the DRC Copperbelt (modified after Batumike et al., 2007) and detailed stratigraphic column of the Grand Conglomérat (Ng 1.1) at Kamoa. Copper mineralisation (red) is in the basal diamictite unit (Ng 1.1.1).

The copper deposits in the Zambian Copperbelt are generally stratiform and are grouped into argillite- (70%) and arenite-hosted (30%) types (Selley et al., 2005). The distribution, geometry, and size of deposits are fundamentally controlled by early sub-basin fault architecture and the availability of both in situ and mobile reductants, the distribution of which is linked to basin structures (Selley et al., 2005). Two mineralogical ore assemblages are predominant in the Zambian Copperbelt. The volumetrically dominant type consists of disseminated Cu—Co sulphides; less important vein-hosted Cu—Co sulphides are also present (Selley et al., 2005; Sillitoe et al., 2017a). The most typical sulphide assemblage in the deposits is chalcopyrite-bornite with subsidiary chalcocite and pyrite. The Zambian Copperbelt also contains ubiquitous, but volumetrically minor, Cu—U—Mo-(Au) mineralisation in post-folding veins, which locally form deposits (e.g., Kansanshi; Torrealday et al., 2000; Broughton et al., 2002; Hitzman et al., 2012). Based on the results of 15 Re—Os molybdenite age determinations from Cu ± Co deposits across the Zambian Copperbelt, Sillitoe et al. (2017a) suggested that both the disseminated and veinlet mineralisation styles were precipitated together in a 50- myr (~540–490 Ma) time span during the later stages of the Lufilian collisional orogeny. In the DRC, mineralisation is hosted primarily in the Mines Subgroup, in transgressive and regressive supratidal to subtidal sedimentary rocks deposited under low-energy, shallow-water conditions (Cailteux, 1994).

3. Local geology of the Kamoa area

The Kamoa deposit occurs in a gently folded region approximately 10 km west of Kolwezi, above a regionally NNE-trending, broadly south-plunging basement block that crops out to the north as the Nzilo inlier (Fig. 3). In more detail, the deposit is proximal to two localised anticlines, the Kamoa and Makalu domes, situated between the West Scarp fault and the Kansoko trend (Fig. 3). Two main rock units are present at Kamoa: the Mwashya Subgroup (possibly the equivalent to the Kanzadi Fm. of the upper Roan Group described by Cailteux et al., 2007) and the overlying Grand Conglomérat (Mwale Fm.; lowermost Nguba Group). The domes form erosional windows exposing the paleo-redox boundary between underlying, hematitic (oxidised) Mwashya Subgroup sandstone/siltstone, and overlying and sulphidic (reduced) Grand Conglomérat diamictite (Broughton and Rogers, 2010). The Kamoa deposit area is deeply weathered and thickly covered by overburden composed of Kalahari sands, residual soil, and saprolite. Owing to the dearth of outcrop, almost all geological information has been obtained from core.

Six main lithostratigraphic units are identified at Kamoa: Kibaran basement rocks (ca. 1380 -1370 Ma; Tack et al., 2010), basal conglomerate ("Poudingue"), hematitic feldspathic sandstone/siltstone with local pebbly conglomerate beds of the Mwashya Subgroup

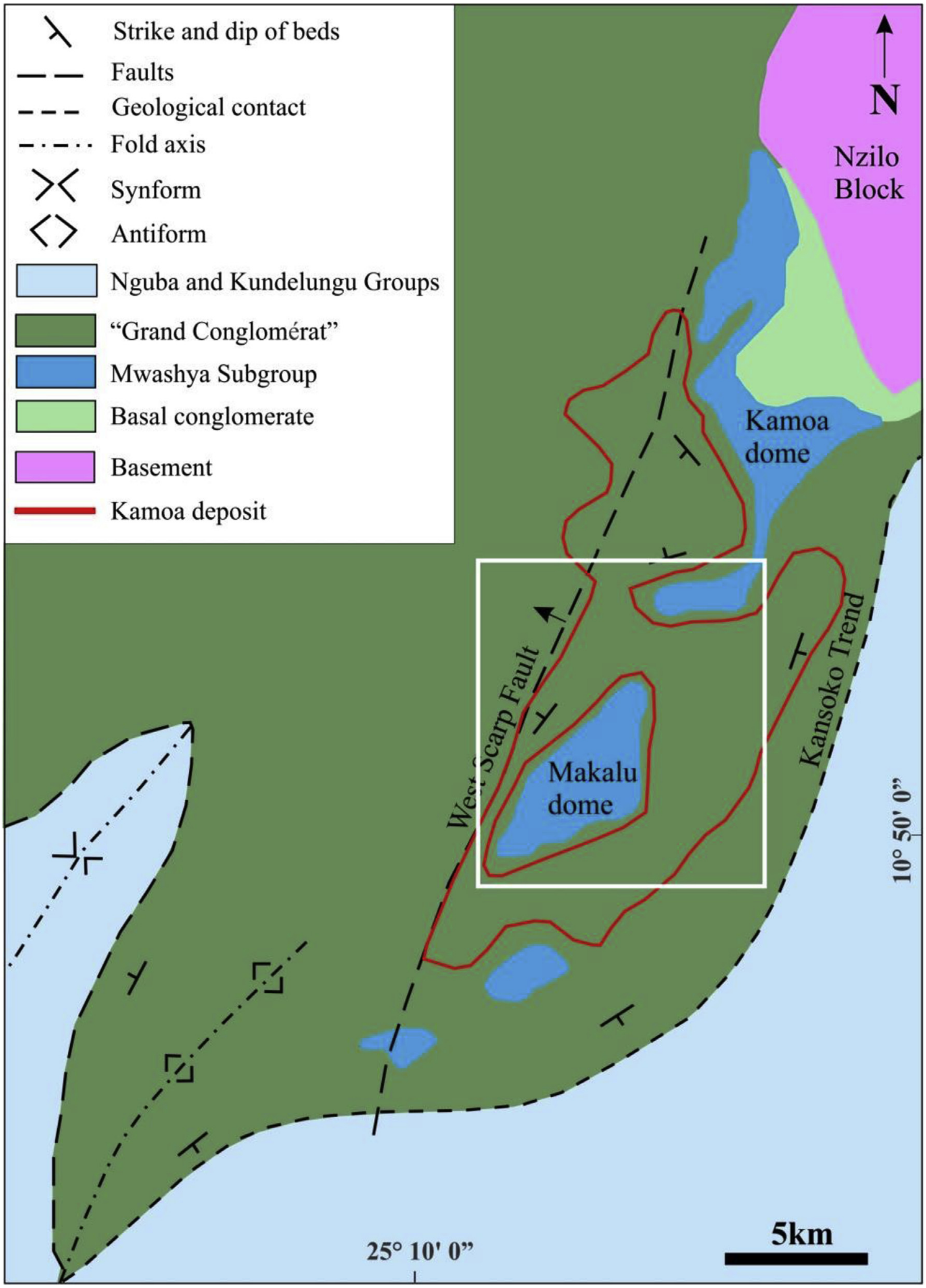

Fig. 3. Simplified geologic map of the Kamoa area. The Mwashya Subgroup and overlying Nguba Group rocks dip gently ∼5–20° away from the domes. East of Kamoa is the north-northeast-trending Kansoko trend, a regional structure interpreted as marking the approximate western edge of the salt-influenced External-Fold-and-Thrust Belt. The Kamoa deposit is outlined in the red line. Box indicates area depicted in Figs. 4 and 6. Modified after Broughton and Rogers (2010).

(uppermost Roan Group), diamictite (Grand Conglomérat) and siltstone-sandstone of the lowermost Nguba Group, and mafic volcanic rocks locally intercalated with these strata (Broughton and Rogers, 2010).

Basement rocks exposed north of Kamoa in the Nzilo block (Fig. 3) consist of Kibaran-aged quartzite, weakly metamorphosed ferruginous siltstone and sandstone, sandstone, mafic rocks, carbonaceous phyllite, and dolostone (Schmandt et al., 2013). In that northern area, the

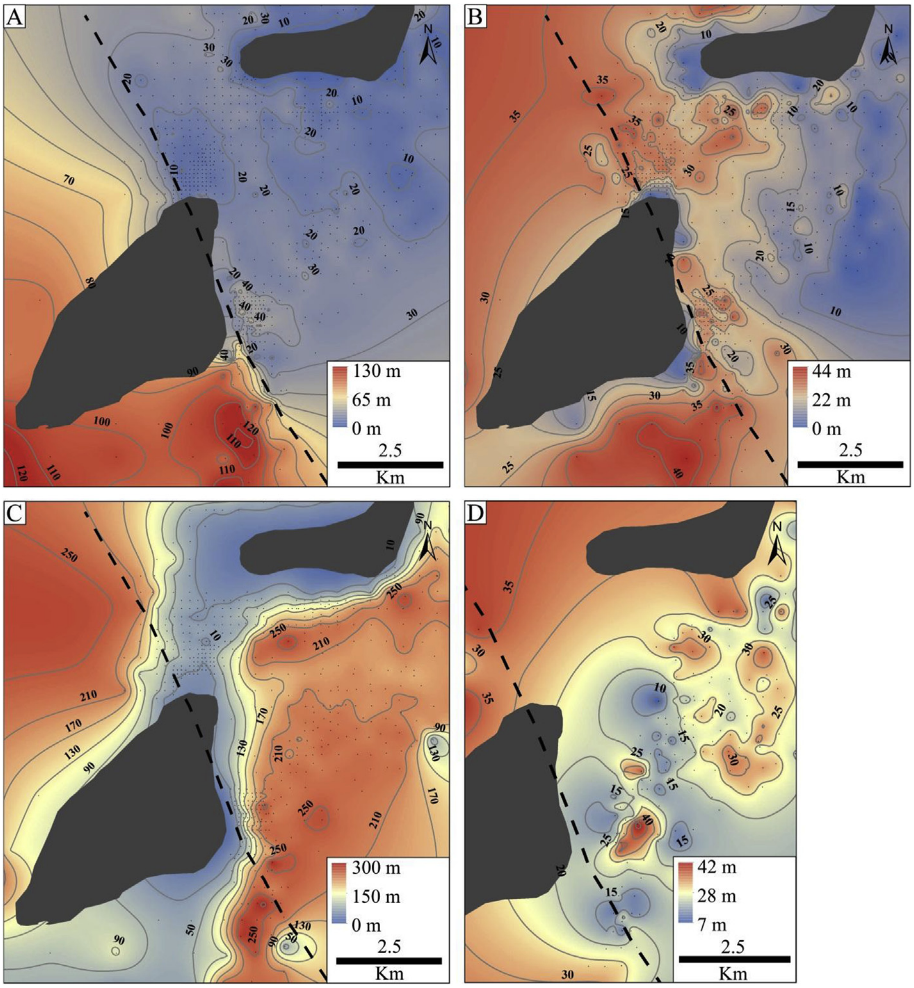

Fig. 4. Isopach maps superimposed with contour lines (true thickness, in metres) of stratigraphic units of the Grand Conglomérat at Kamoa. These are constructed based on interpolations between data points. Note that the apparent "thinning" of units, particularly Ng1.1.3 and 1.1.4, proximal to the domes (dark grey) is due to preservation, the domes are defined by sub-cropping Mwashya sandstones that underlie the Grand Conglomérat. Black dashed lines indicate the approximate location of the Mupaka fault, based on the abrupt change of stratal thickness of stratigraphic units. The area presented is the same in all maps except for (D). A) Thickness of the basal diamictite (Ng 1.1.1). B) Thickness of the lower laminated pyritic siltstone/sandstone (Ng 1.1.2). C) Thickness of the middle diamictite package (Ng 1.1.3). D) Thickness of the upper laminated pyritic siltstone/sandstone unit (Ng 1.1.4). (2-column fitting image; print in color).

Kibaran (basement) is unconformably overlain by the basal conglomerate, and the latter variably by the Mwashya Subgroup or the Nguba Group (François, 1973). In the Kamoa area, the Mwashya Subgroup consists of texturally immature, thickly bedded (20 cm–1 m) hematitic feldspathic sandstone and thinly interbedded hematitic siltstone and sandstone. Most drilling in the deposit area has intersected only the upper 5–15 m of the Mwashya rocks, hence its full extent and character is incompletely known.

The Mwashya rocks are sharply but conformably overlain by diamictites of the Grand Conglomérat (Mwale Formation, base of the Nguba Group), that here include lesser siltstone and sandstone beds.

Most previous work concluded that the Grand Conglomérat had a glacio-marine origin (Binda and Van Eden, 1972; Selley et al., 2005; Wendorff and Key, 2009; Master and Wendorff, 2011). The most recent research by Kennedy et al. (2018) based on borehole core from the Kamoa area suggests that the Grand Conglomérat rocks are not tillites and do not record an ice-contact, but are interpreted as mass flow (debrites) within thick (< 3 km) successions of genetically-related sediment gravity flow facies (olistostromes, slumps, and turbidites) deposited in deep-water within rapidly subsiding rift basins.

Mafic volcanic rocks occur within the Mwashya Subgroup and at the base of the Grand Conglomérat in the northeast of the Kamoa deposit (Kampunzu et al., 1991; Key et al., 2001; Cailteux et al., 2007).

The western edge of the Kamoa deposit is offset by the west-down West Scarp fault (Fig. 3). Across this fault, the lack of thickness and facies variations in stratigraphic units suggest that the fault was not active during the deposition of the upper Mwashya Subgroup and lower Nguba Group (Broughton and Rogers, 2010; Schmandt et al., 2013). The Kansoko trend, a regional north-northeast-trending structure identified from aeromagnetic data east of Kamoa, appears to be a major, east-side-down normal fault that is now marked by an east-dipping monocline. This feature appears to represent the western structural edge of the classical fold-and-thrust belt: to the east, the complete succession of the Mwashya Formation and megabreccia-hosted R.A.T., Mines, Dipeta subgroups occur, whereas in the Kamoa area only the top of the Mwashya Formation has been observed (Broughton and Rogers, 2010; Schmandt et al., 2013; Kennedy et al., 2018).

The redox boundary at the contact between the Grand Conglomérat and the immediately underlying hematitic Mwashya Subgroup is a major control for copper sulphide precipitation (Broughton and Rogers, 2010). Three sequential types of hydrothermal alteration are recognised in the Kamoa deposit: potassic, silicic and magnesian alteration (Schmandt et al., 2013), these alterations have been reported in different areas such as the Shanika syncline in the Tenke Fungurume Mining District (Mambwe et al., 2017) as well as in the Fishtie deposit (Hendrickson et al., 2015).

4. Detailed stratigraphy and lithofacies of the Grand Conglomérat at Kamoa

The Grand Conglomérat comprises four lithofacies at Kamoa: diamictite, laminated pyritic siltstone/sandstone, turbiditic lenses with conglomerates and mafic volcanics (Schmandt et al., 2013; Kennedy et al., 2018). Diamictite and siltstone are volumetrically predominant (Fig. 2) while turbiditic lenses with conglomerates and mafic volcanics are volumetrically minor. Six stratigraphic units have been identified from the bottom to the top: (1) the basal diamictite (Ng 1.1.1); (2) the lower laminated pyritic siltstone/sandstone, (Ng 1.1.2); (3) the middle diamictite, (Ng 1.1.3); (4) the upper laminated pyritic siltstone/sandstone, (Ng 1.1.4); (5) the upper diamictite (Ng 1.1.5); and (6) the uppermost diamictite (Ng1.1.6) (Schmandt et al., 2013; Kennedy et al., 2018).

An overview of the various lithologic and stratigraphic units of the Grand Conglomérat is presented with a particular focus on lateral thickness variations as this will contribute to a greater understanding of the sedimentary and tectonic framework (Twite, 2016). More than 800 boreholes were used to construct isopach maps and examine stratigraphic and lithological variations in the Kamoa area. Isopach maps of different stratigraphic units of the Nguba Group were established based on their true thickness (Fig. 4).

The basal diamictite (Ng 1.1.1) is the main host for the Kamoa copper orebody. It shows an abrupt thickness change across the Mupaka fault from 40 to 120 m thick in the southwest to 3–35 m thick in the northeast (Fig. 4 A). The basal diamictite comprises three subunits: from the bottom to the top, the lower basal diamictite (Ng 1.1.1.1), the intercalated siltstone/sandstone unit (Ng 1.1.1.2) and the upper basal diamictite (Ng 1.1.1.3) (Fig. 2).

The lower basal diamictite (Ng 1.1.1.1) consists of olive, maroon, and pale grey diamictite that contains an average of 20–35% of pebble-size clasts. It is poorly mineralised and sandy at its base. Generally of 5–25 m thickness, this unit thins or pinches out east of the Mupaka fault and thickens (up to 40–80 m) west of the fault. In the northeastern part of the Kamoa area, the lower basal diamictite varies from 1 to 5 m thick, is absent or thinner in the east-central part of the deposit, and varies from 5 to 20 m thickness in the central part. The pebbles and larger clasts are sub-angular to sub-rounded and their size is generally less than 10 cm, excluding large mafic igneous clasts, which are up to 50 cm in diameter. The clasts are poorly sorted and composed of quartzite, quartz, mafic igneous rock, and sandstone. The presence of a hematitic matrix, commonly just above the contact between underlying Roan Group sandstone, identifies a maroon oxide facies. The percentage of large clasts and their sizes within this unit are higher (25–35%) east of the Mupaka fault than to its west (7–15%) where the distinction between the lower basal diamictite and the upper basal diamictite is difficult. West of the Mupaka fault, the amount of intermediate siltstone/sandstone layers in the basal diamictite increases significantly.

The intercalated siltstone/sandstone unit (Ng 1.1.1.2) consists primarily of interbedded olive, grey to dark grey siltstone and sandstone with local bands of small-pebble conglomerate. It is generally well mineralised, but discontinuously distributed, and absent or less than 2 m thick in the northeastern part of the deposit area. Its thickness increases abruptly west of the Mupaka fault to 5–20 m.

The upper basal diamictite (Ng 1.1.1.3) is composed of medium to dark olive-grey diamictite with an argillaceous, silty, chloritised matrix. Its thickness varies from 3 to 15 m east of the Mupaka fault and up to 30–60 m thick west of the fault where it is intercalated with siltstone and sandstone layers. The diamictite generally contains 10–20% pebble-size clasts composed of unsorted quartzite, argillite, and mafic clasts that range from 2 to 10 cm in diameter.

The basal diamictite (Ng 1.1.1) is overlain by the lower laminated pyritic siltstone/sandstone (Ng 1.1.2), also called the "Kamoa pyritic siltstone" (KPS). It comprises pale to medium grey, greenish black laminated to bedded mudstone/siltstone with local large clasts, and intercalated sandstone layers with a mixture of massive, thickly bedded and small-pebble conglomerate bands. This unit locally contains diamictite (5–15% of pebble-size clasts) in the northeast area. The thickness of the KPS changes abruptly across the Mupaka fault, from 0 to 15 m thick east of the fault to 40 m thick west of the fault (Fig. 4 B). In the deposit area, the contact between the KPS and the basal diamictite is generally sharp and marked clearly by 30–50 mm of thin laminations, considered as stratigraphic markers.

The middle diamictite (Ng 1.1.3) is generally a medium-to dark grey, diamictite with 20–40% pebble-size or larger clasts (5 cm–1 m diameter); its thickness varies from 150 to 250 m. The isopach map for this unit does not show any abrupt thickness changes across the Mupaka Fault (Fig. 4 C).

The upper laminated pyritic siltstone/sandstone (Ng 1.1.4) contains pale, medium to greenish grey, laminated pyritic siltstone with intercalations of pale grey sandstone and minor small-pebble conglomerate, and varies from 5 to 25 m thick. The isopach map for this unit shows only a subtle thickness variation (Fig. 4 D).

The upper diamictite unit (Ng 1.1.5) is composed of pale greenish grey, diamictite with 7–15% pebble-grade or larger clasts of quartzite, mafic rock, argillite, and range in size from 0.5 to 5 cm. This unit ranges from 200 to 350 m thick and is intercalated with thin to thick layers of sandstone and siltstone.

A 0.5- to 15 m-thick sandstone bed forms the base of the uppermost diamictite unit (Ng1.1.6). This unit is composed of pale greenish-grey diamictite with 7–20% pebble-size or larger clasts of quartzite, mafic rock, and argillite, intercalated with thick conglomerate, sandstone, and siltstone beds. This unit is preserved only in the deepest holes of the central, eastern and northern area of the deposit (i.e., eroded near domes). The clasts are predominantly composed of quartzite, quartz, and mafic igneous rocks, and range from 5 mm to 15 cm in diameter. The composition of the diamictite of the uppermost diamictite unit (Ng 1.1.6) is similar to that of the upper diamictite (Ng 1.1.5).

5. Structural geology

The Kamoa deposit occurs on the southerly extension of a basement inlier ("basement high") between two major north-northeast trending structures (Fig. 3; Parker et al., 2013). East of the deposit is the Kansoko trend, a major regional north-northeast trending structure identified based on the aeromagnetic data. To the west is a prominent escarpment and a magnetic feature named the West Scarp Fault (Broughton and Rogers, 2010). Within this overall north-northeast trending structural corridor occur several second-order anticlines ("domes") where the Grand Conglomérat is eroded and the Mwashya sandstone is subcropping (Fig. 3).

In the southern part of the Kamoa deposit, an abrupt change in stratigraphic thickness of the basal diamictite (Ng 1.1.1) is observed. This change ranges from 40 to 60 m in true thickness (Fig. 4 A). A minor change in the thickness of the lower and upper laminated pyritic siltstone/sandstone (Ng 1.1.2 and Ng 1.1.4) is also observed across the Mupaka fault, ranging from 10 to 15 m of true thickness (Fig. 4 B and D).

Steeply dipping bedding, soft-sediment deformation and syn-sedimentary mesoscopic faults are common throughout the Kamoa area, especially in lithologies in close proximity to the Mupaka fault (Fig. 5). The steep bedding near this fault in one borehole strikes NNW/SSE, whereas the typical regional bedding strikes NNE/SSW. The orientation of the Mupaka fault is oblique to the trend of the domes and coincides with an area of elevated copper grade (Fig. 6).

Minor mesoscopic faults (Fig. 5C–F) occur, and are commonly subvertical in sub-horizontal beds adjacent to the steep bedding while they are gently-dipping in steep bedding. It is suggested here that they predate the formation of the steep bedding.

6. Mineralisation

Kamoa is currently understood to be a redox-controlled sedimentary-rock-hosted stratiform copper deposit that developed at a redox boundary between the Mwashya Subgroup and the Grand Conglomérat (Broughton and Rogers, 2010; Hitzman et al., 2012; Schmandt et al., 2013; Broughton, 2014).

The Mwashya Subgroup rocks contain specular haematite as the dominant mineralisation. Occasional fine- and coarse-grained bornite/chalcocite associated with rare native copper is observed in the top

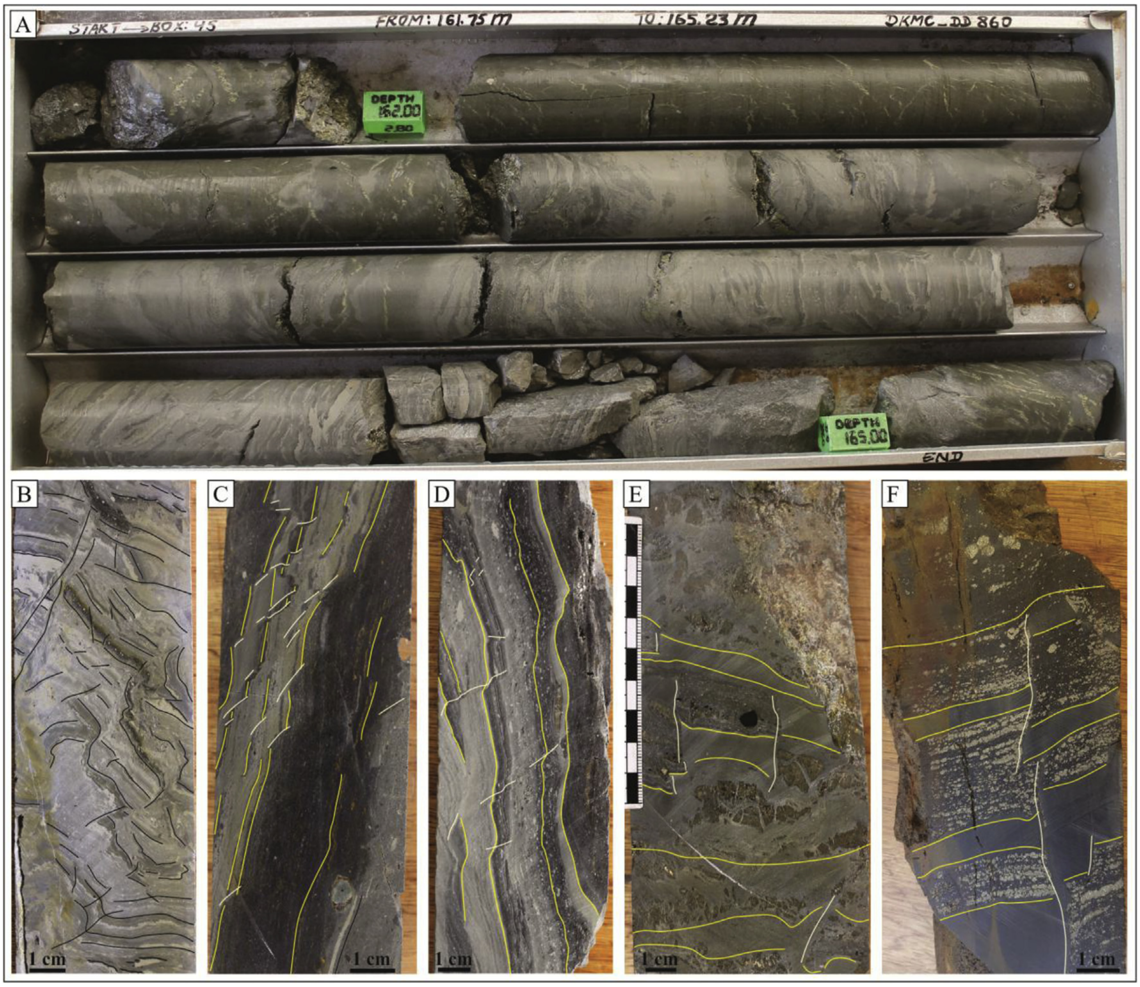

Fig. 5. Structural features, lithologies and mineralisation in close proximity to the Mupaka fault. A) Soft sediment deformation and syn-sedimentary mesoscopic faults. DKMC_DD860, 161.75–165.23 m. B) Slump folds and mesoscopic faults (in black lines). DKMC_DD860, 164.30–164.45 m. C) Siltstone/mudstone displaying steep bedding, abundant fine-grained bornite, and traces of chalcopyrite. Low-angle healed normal microfaults. DKMC_RD432, 300.14–300.31 m. Borehole azimuth 360°; inclination −90°. D). Steep bedding associated with fine-to coarse-grained bornite and traces of chalcopyrite in siltstone/mudstone. Healed mesoscopic faults show predominantly normal displacement relative to steep bedding. DD860, 173.20 m - 174 m. Borehole azimuth 270°; inclination −90°. E) Steep and healed mesoscopic faults are defined by offset of beds. DKMC_DD860, 165.75–165.90 m. F) Sub-vertical, healed normal mesoscopic faults in shallowly dipping beds (interpreted as syn-sedimentary features). Pyrite occurs possibly during the deposition of the host rock. DKMC_DD860, 125.02–125.14 m. Yellow lines show bedding and white lines highlight mesoscopic faults.

three metres immediately below the contact between the basal diamictite and the Mwashya Subgroup rocks. In addition traces of cuprite, malachite and chrysocolla can be observed in this zone (Twite, 2016).

The lower basal diamictite generally contains only minor copper sulphides (< 1 wt% Cu), but in boreholes south of Makalu dome the copper grade is locally higher (Fig. 7). Abundant copper sulphides are generally present only in the upper basal diamictite and in the locally intercalated siltstone/sandstone that overlies the lower basal diamictite. The lowermost 3–5 m of the lower laminated pyritic siltstone/sandstone generally contains fine-grained pyrite, but locally contains copper minerals.

The mineralised zone in the basal diamictite is 0.5–7 m thick in the northeastern part of the deposit (east and south of Kamoa dome; north of Makalu dome) and from 5 to 17 m thick in the southeastern part (south and southeast of Makalu dome). The copper content of the mineralised interval varies from 1 to 8 wt% (locally to 15 wt%). In most boreholes, the grade profile shows a sharp transition from < 0.5 wt% Cu to > 1 wt% Cu at the bottom of a zone with a continuous Cu grade of > 1 wt% (Fig. 7).

Within the basal diamictite, chalcopyrite is the most abundant copper sulphide (~50%) followed by bornite (~30%) and chalcocite (~20%). These copper minerals occur as fine- and coarse-grained disseminations as well as in the rims of clasts. Minor pyrite is observed above the mineralised zone, it occurs as framboidal pyrite as well as coarse-grained euhedral pyrite. Traces of native copper are also present at the bottom of the basal diamictite.

The lower laminated pyritic siltstone/sandstone (Ng1.1.2) and the upper laminated pyritic siltstone/sandstone (Ng1.1.4) contain abundant pyrite (15–30%). Pyrite occurs as framboidal (70%) and euhedral grains (30%) in the rock. The size of framboids varies from 3 to 40 µm while the size of the euhedral pyrite ranges from 25 µm to 1 mm, and occasionally up to 4 mm in size. At the base of the lower laminated pyritic siltstone/sandstone, the replacement of framboidal pyrite by copper sulphide is generally observed (Schmandt, 2012; Twite, 2016). The middle diamictite, the upper diamictite and the uppermost diamictite contain some pyrite (framboidal and euhedral grains), trace pyrrhotite, and rare chalcopyrite.

Vertical ore sulphide zonation is generally present within the Kamoa deposit and correlates well with an overall decrease in Cu/S ratio from the bottom to the top of the mineralised zone. From the contact between the Mwashya Subgroup and the Grand Conglomérat upward, the hypogene mineral zonation typically consists of specular haematite

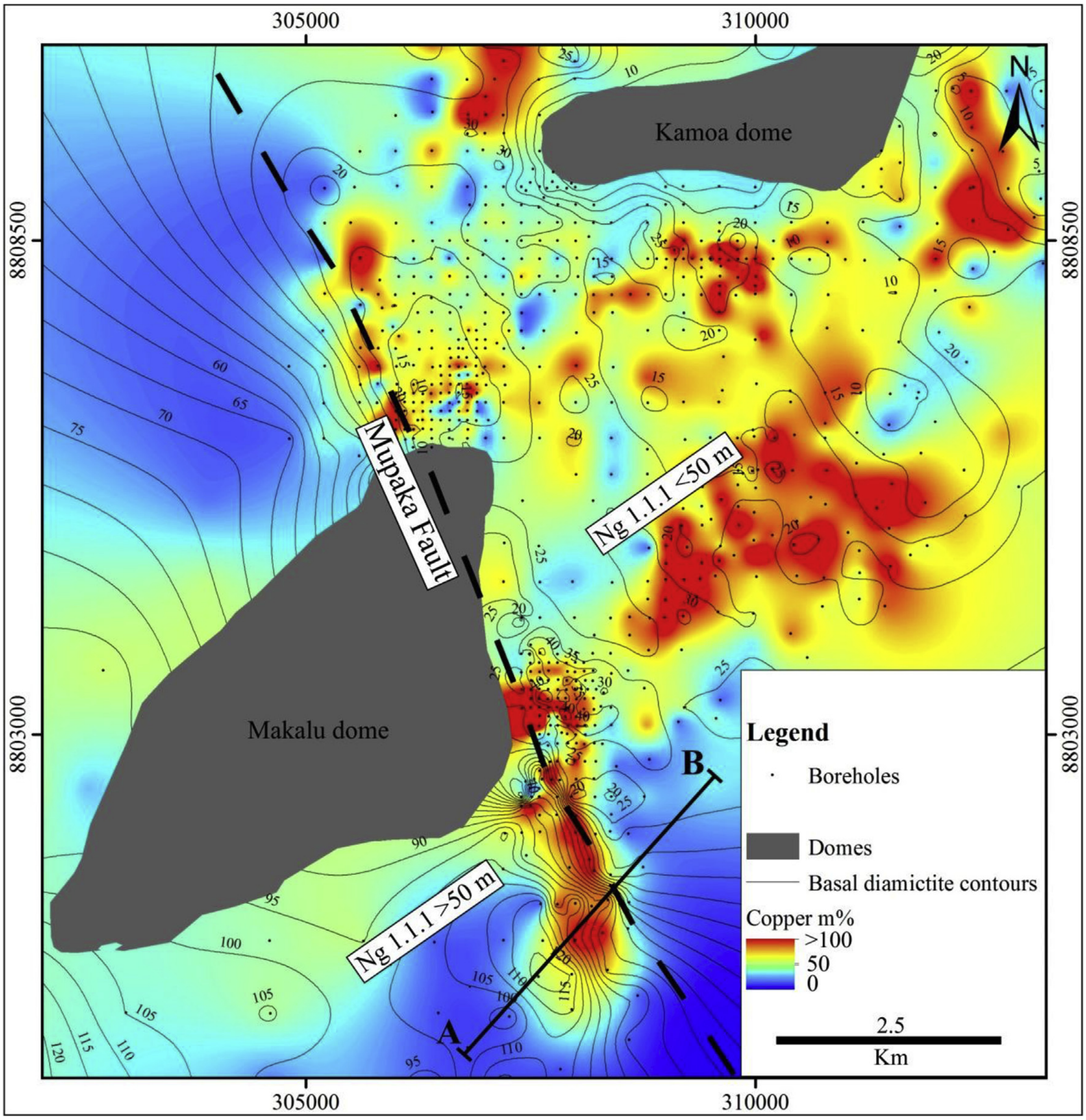

Fig. 6. Isopach map (true thickness, in metres) of the basal diamictite (Ng 1.1.1) with superimposed copper grade distribution from boreholes. Black points are locations of borehole data used to construct the map. The black dashed line (Mupaka fault) shows the approximate location of the zone of abrupt change in stratal thickness of the basal diamictite. There is a general coincidence of the Mupaka fault with high-grade copper. Line A - B shows the location of the section line depicted in Fig. 7. Copper m% in the legend represents the thickness of the ore zone multiply by the Cu grade (%).

associated with local native copper, chalcocite, bornite, chalcopyrite, and pyrite (Broughton and Rogers, 2010; Schmandt et al., 2013). Sphalerite is weakly developed above Cu zones where it is associated with pyrite (Twite, 2016). There is no abrupt change in the vertical mineral zonation; an overlap between sulphides is generally observed. The stratigraphically lower, more copper-rich sulphides partially replace the overlying, more copper-poor sulphides (Twite, 2016). Lateral zoning is poorly understood.

The boreholes investigated for this study show two main stratigraphic positions of continuously mineralised zones grading over 1 wt% Cu: one to the east of the Mupaka fault where copper mineralisation is located in the intercalated siltstone/sandstone, in the upper basal diamictite and locally in the lower laminated pyritic siltstone/sandstone. The other ore zone is observed to the south and southwest of the Mupaka fault where copper mineralisation is located at the base of the lower basal diamictite. Thus, the Mupaka fault appears to be the boundary between the two separate ore zones (Fig. 7).

The Mupaka fault also correlates well with elevated copper grades (Fig. 6). The highest copper grades occur in the intercalated siltstone/sandstone beds in holes close to the Mupaka fault, and there the thickness of the ore zone varies from 4 to 12 m, and locally up to 17 m.

7. Discussion

Understanding of the factors that controlled the distribution and grade of copper in the recently discovered Kamoa deposit is critical in the well-informed mineral exploration environment. To set the Kamoa deposit into a regional context, it has been compared to some deposits in the Zambian Copperbelt based on their stratigraphic architecture and mineralisation styles (Fig. 1).

7.1. Syn-sedimentary rifting and the recognition of the Mupaka fault at Kamoa

Tectono-stratigraphic models for the Roan Group in the CACB are best developed in the Zambian Copperbelt, where the Roan is

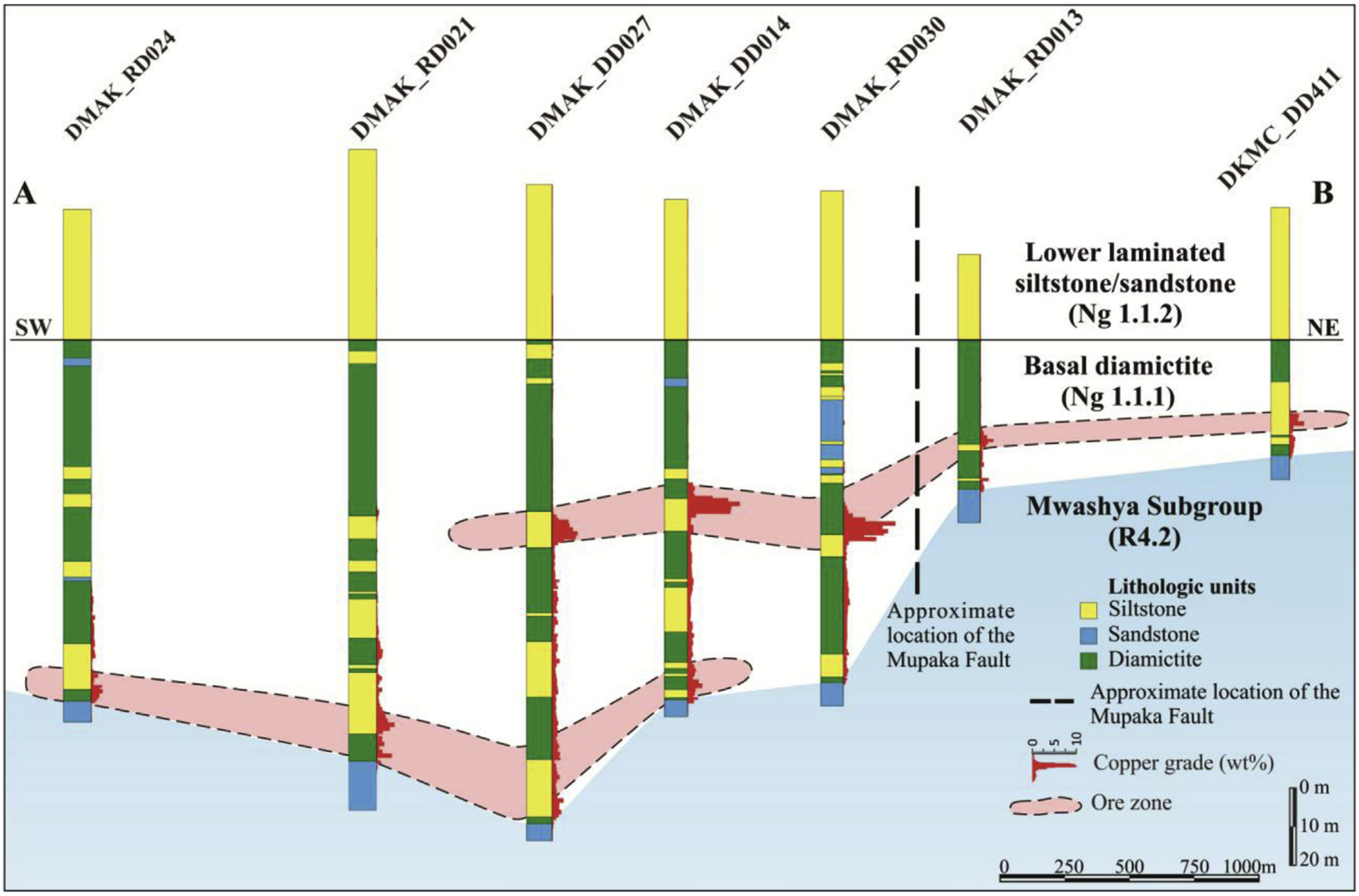

Fig. 7. Section line across the Mupaka fault, 'hung' from the base of the lower laminated pyritic siltstone/sandstone (Ng 1.1.2). Northeast of the Mupaka fault, the siltstone-sandstone package is much thinner than to its southwest, and the number of intercalated sandstone, siltstone, and diamictite layers is much higher on the southwestern side of the fault.

autochthonous and basement rocks are widely exposed and intersected in boreholes. The models are similar to those developed from studies of the Phanerozoic intracontinental rifts, where rift evolution generally progressed from small isolated sub-basins bounded by a complex array of discontinuous faults, to a system of broader, interconnected depocentres controlled by master faults (Selley et al., 2005; Muchez et al., 2010; Hitzman et al., 2012). Syn-sedimentary normal faults have been documented as first-order ore controls at several deposits in the Zambian Copperbelt, such as Mwambashi B, Chambishi, Konkola, and Musoshi (Selley et al., 2005). At the Fishtie deposit (southeast of the Zambian Copperbelt in the Central Province of Zambia), syn-sedimentary faults have been reported to control both ore distribution and thickness and facies variations in the Grand Conglomérat and Kakontwe Limestone formations (Hendrickson et al., 2015).

Unlike most of the deposits in the Zambian Copperbelt, where the exposure of basement rocks helps to identify growth faults (Selley et al., 2005), depth to basement and the thickness and character of autochthonous Roan Group are essentially unknown below the classical, allochthonous Mines Subgroup-hosted orebodies of the DRC Copperbelt. The evidence presented here for Kamoa, in an autochthonous setting at the western edge of the DRC Copperbelt (Key et al., 2001; Broughton and Rogers, 2010), suggests that the presence of a significant syn-sedimentary fault controlled both facies and thickness variation in the lower part of the Grand Conglomérat, as well as the localisation of ore (Fig. 8).

The identification of the Mupaka fault represents an important development in understanding the genesis of the Kamoa copper deposit. This fault trends NNW/SSE, whereas regional bedding generally strikes NNE/SSW. The thickness of stratigraphic units and the lithofacies of the basal diamictite vary across this fault (Fig. 8). Steeply dipping bedding, soft-sediment deformation and syn-sedimentary mesoscopic faults are common throughout the Kamoa area, especially in lithologies in close proximity to the Mupaka fault (Fig. 5). These characteristics indicate that this linear feature is a syn-sedimentary intrabasinal normal fault that was active during deposition of the Grand Conglomérat.

The Mupaka fault is interpreted to represent a large-scale intrabasin fault developed or reactivated during rifting associated with the deposition of the Grand Conglomérat (Fig. 8) and, at Kamoa, the deposition and emplacement of mafic volcanic rocks. The abundance of syn-sedimentary deformation structures suggests that the base of the Grand Conglomérat was affected by seismicity and gravitational instability associated with slopes, and the preservation of thick diamictites at Kamoa was facilitated by rapid subsidence of fault-bounded depocentres (Kennedy et al., 2018). Mambwe et al. (2019) reported similar syn-sedimentary deformation structures at the Shanika syncline in the Tenke Fungurume Mining District.

7.2. Mineralisation

The general model for sedimentary-rock hosted stratiform copper deposits such as Kamoa and more broadly the CACB deposits involves redox-controlled deposition of copper and copper-iron sulphides from saline ore fluid migrating into reduced (host) rocks from underlying oxidised (source) rocks (Kirkham, 1989; Brown, 1997; Hitzman et al., 2005; Robb, 2005; De Waele et al., 2006). At Kamoa, haematite-bearing sandstone and siltstone of the Mwashya Subgroup form the oxidised lower strata, and the pyritic rocks of the basal diamictite (Ng1.1.1) form the reduced host rock. A stratiform zonation is observed within the

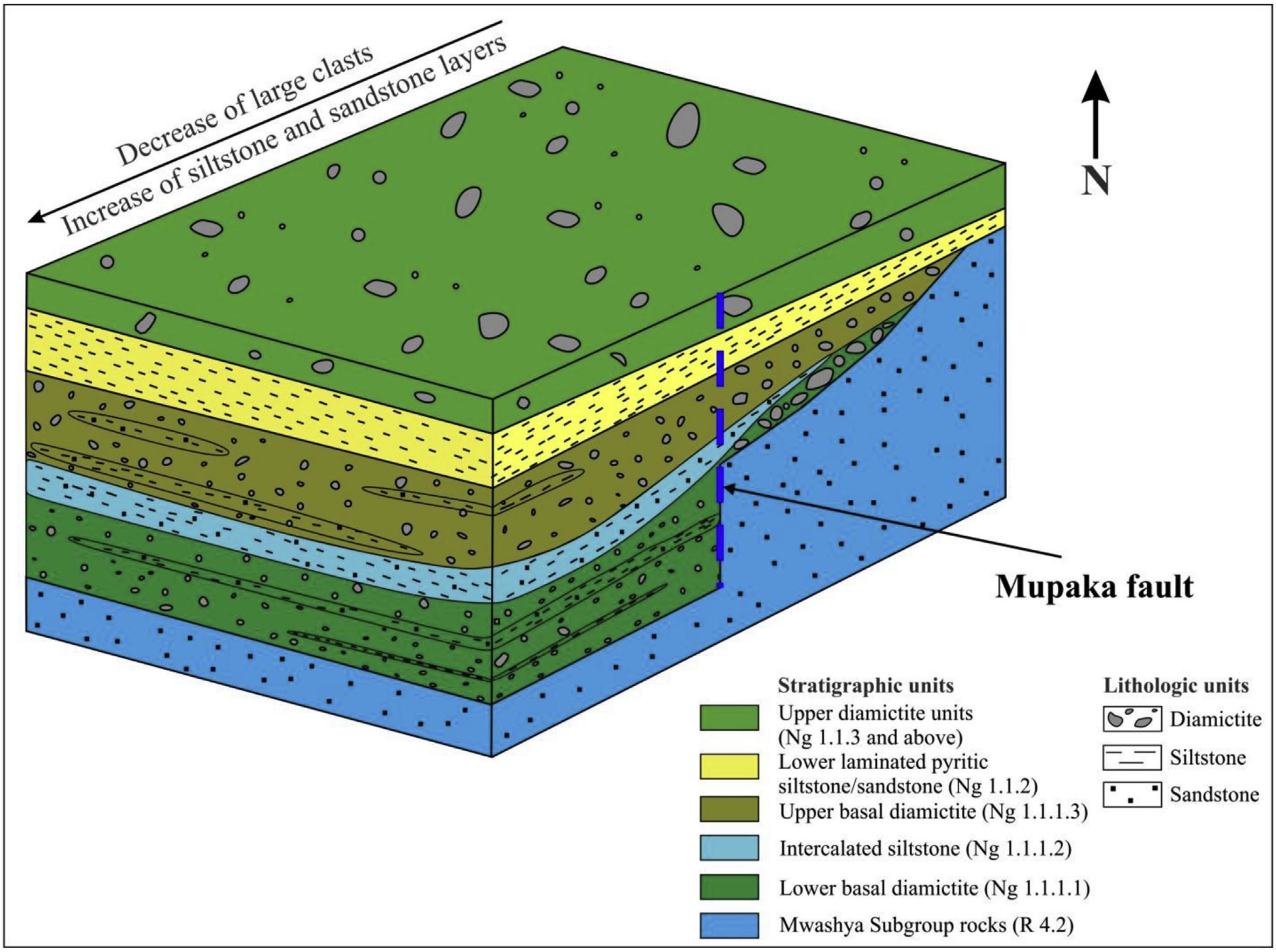

Fig. 8. Simplified stratigraphic model for the Kamoa deposit, based on facies types and stratal thickness of stratigraphic units. The abundance and size of clasts decreases from northeast to southwest. Thickness and number of siltstone and sandstone layers increase to the WSW, across the Mupaka fault.

Kamoa orebody showing, from bottom to top, copper-rich sulphides, followed by (progressively/sequentially) less copper rich sulphides and pyrite (Broughton and Rogers, 2010; Schmandt, 2012; Broughton, 2014; Twite, 2016) in both the DRC and Zambian Copperbelts (Cailteux et al., 2005; Selley et al., 2005). Numerical modelling by Muchez and Corbella (2012, 2016) provides a useful reactive transport model for mineralogical zoning and the sequence of mineralisation seen principally in the DRC Copperbelt. Muchez and Corbella (2016) consider that based on the work of Schmandt et al. (2013), their model can be applied to Kamoa. However, as they have noted, the specific stratigraphic units and therefore lithologies that are host to ore are different at Kamoa compared to the rest of the Katangan Copperbelt.

The mineralisation at Kamoa is broadly stratiform, but thickness variations reveal important clues about potential focal points for fluid flow and high-grade mineralisation. The thickness of the mineralised zone ranges from 0.5 to 7 m in the northeastern part of the deposit and from 5 to 17 m in the southwest part. The copper grade map of the Kamoa deposit illustrates a structural control on the grade distribution, the area of highest-grade copper trends north-northwest, and is coincident with the north-northwest trending interpreted syn-sedimentary Mupaka fault (Fig. 6). This suggests that the NNW-trending Mupaka fault may have been an important transport path for hydrothermal fluids, and as such would represent a primary mineralising structure in the Kamoa deposit (Fig. 9 B). The importance of the fault acting as a fluid pathway, in comparison to the role of lithological variation or alteration of rocks in proximity to the fault requires further study.

Faults of similar age were reported by Hendrickson et al. (2015), who suggested that hydrothermal fluids at the Fishtie deposit were directly channelled upwards into the Grand Conglomérat along high-angle syn-sedimentary normal faults. In the Zambian Copperbelt, the distribution and geometry of the ore zones are controlled by early sub-basin fault architecture (Selley et al., 2005; Hitzman et al., 2012). McGowan et al. (2006) suggested that these faults were probably important transport paths for the hydrothermal fluids, both during diagenesis and deformation when the faults were inverted, thus these structures do not specify the timing of copper mineralisation (Sillitoe et al., 2017b).

Timing of ore deposition in the CACB is contentious and may have been deposited in several stages that include syn- and diagenetic mineralisation (Unrug, 1988; Selley et al., 2005; Cailteux et al., 2005; Hitzman et al., 2012; Muchez et al., 2015); syn- and post-orogenic mineralisation (Torrealday et al., 2000; McGowan et al., 2006; Selley et al., 2005; El Desouky et al., 2009; Sillitoe et al., 2017a; Mambwe et al., 2017) and syn-orogenic remobilisation (Haest and Muchez, 2011; Torremans et al., 2013; Turlin et al., 2015). A multistage origin of copper mineralisation has been recognised for the Kupferschiefer mineralisation (Alderton et al., 2016). The localisation of high-grade mineralisation by the Mupaka fault at Kamoa, as elsewhere does not in itself constrain timing of mineralisation. Nonetheless it further underscores an important link between extensional fault architecture and

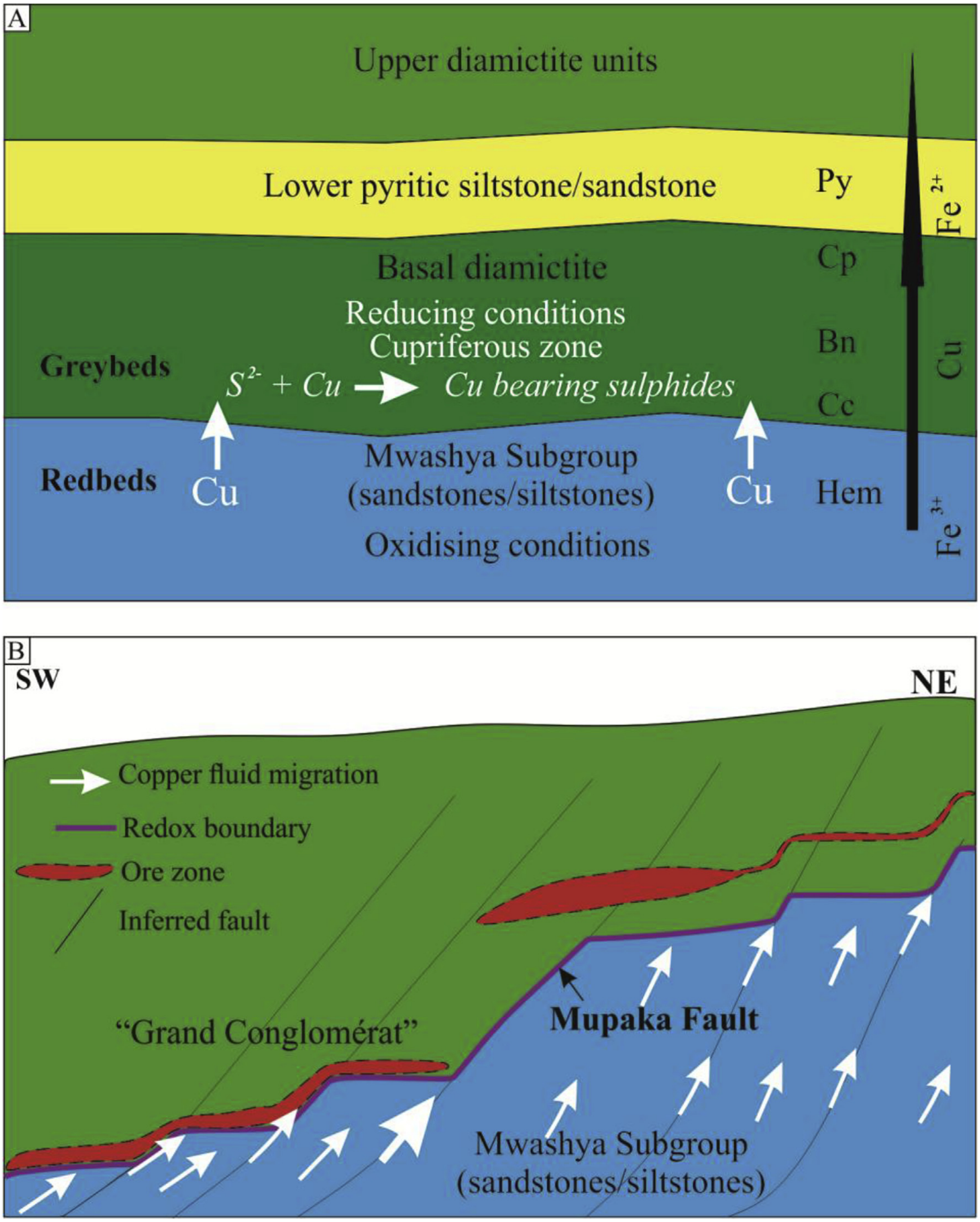

Fig. 9. A) Schematic diagram showing the current understanding of the origin of the Kamoa deposit. Copper mineralisation occurs where ore fluid encountered a reductant in the basal diamictite of the Grand Conglomérat. The lower laminated pyritic siltstone/sandstone and the upper diamictite units are unmineralised (Ng 1.1.2 and above). Hem, haematite; Cc, chalcocite; Bn, bornite; Cp, chalcopyrite and Py, pyrite. (Broughton and Rogers, 2010; Schmandt et al., 2013). B) Schematic interpretation of metalliferous fluid migration in the Kamoa deposit. Syn-sedimentary faults may have been conduits for copper-mineralising fluids. East of the Mupaka fault, mineralisation is located in the intercalated siltstone/sandstone, in the upper basal diamictite and locally in the lower laminated pyritic siltstone/sandstone (higher in the stratigraphy). West of this structure the ore zone is located at the base of the lower basal diamictite.

localisation of orebodies, similar to that documented in the autochthonous deposits of the Zambian Copperbelt at the other extremity of the CACB.

8. Conclusions

The recently discovered Kamoa deposit in DRC is hosted by strata of the lowermost Nguba Group, including diamictite and related sandstone and siltstone of the Grand Conglomérat. The presence of a normal fault active during deposition of the Grand Conglomérat in the area of the Kamoa deposit is strongly suggested by evidence of basin-floor topography (slopes, recorded by sedimentary structures indicating gravitational instability) and marked stratigraphic thickness changes across a linear feature (the Mupaka fault). Ore grade and distribution in the

Kamoa deposit appear to have been strongly influenced by this inferred syn-depositional normal fault. The highest-grade ore in the Kamoa deposit is located along the fault, and highlights the important role of syn-sedimentary faults in the distribution of ore in stratiform base-metal deposits.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafrearsci.2018.12.016.

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