The relevance of the sedimentary history of the Grand Conglomerat Formation (Central Africa) to the interpretation of the climate during a major Cryogenian glacial event.

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Abstract

The Cryogenian *Grand Conglomerat* Formation (<765 & >735 Ma) is an association of interbedded glaciogenic, clastic periglacial and non-glacial deposits, topped by the Kakontwe Limestone cap carbonate. These units occur within the Nguba Group of the Katanga Supergroup, deformed in the Pan African Lufilian Arc that separates the Congo and Kalahari cratons. Correlation of regional unconformities and facies distribution suggest that the *Grand Conglomerat* strata were deposited (during and after eruption of flood basalts) in an asymmetrical rift, with a strongly uplifted southern shoulder, and a graded shelf defining the northern margin. Glaciomarine sediments along the southern margin of the Katangan rift are preserved within fan-delta conglomerates supplied from an elevated rift shoulder. By contrast, the northern margin of the rift was the site of continental glaciation with cross-bedded, glaciofluvial and marginal marine sandstones and conglomerates, associated with massive tills (diamictites) that pass laterally towards the south into glaciomarine mixtite interlayered with wedges of dolomitic sandstone. The Kakontwe Limestone cap carbonate is present only in the distal parts of the basin. Its absence in proximal regions is considered to reflect very high rates of sedimentation of fine-grained glaciogenic debris derived from deglaciated source areas. Palaeomagnetic data indicates that the *Grand Conglomerat* glaciogenic sediments were deposited close to the Equator during the Cryogenian. This low-latitude setting, coupled with the absence of a topographical trigger would suggest that glaciation was related to global atmospheric cooling. However, the presence of water-borne, glaciogenic on-shore sediments, and offshore sediments derived from floating glaciers suggests that the ocean during this part of the Cryogenian was not completely frozen. Associations of glaciogenic facies with non-glaciogenic sediments imply glaciation with interglacial periods and gradual deglaciation, instead of severe conditions of permanent sea ice cover and rapid change to the greenhouse environment.

Keywords: Grand Conglomerat; Pan African Lufilian Arc; Neoproterozoic; glaciogenic sedimentation; Snowball Earth; Central Africa

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1. Introduction

The Neoproterozoic-Lower Palaeozoic Katanga Supergroup is exposed in the Lufilian belt (part of the continental system of Pan-African orogenic belts of Africa), and also forms a less deformed plateau molasse/foreland sequence over the Congo Craton (Fig. 1). Katangan sediments were initially deposited in intracratonic rifts related to early Neoproterozoic extension of the ca. 1000Ma Rodinia Supercontinent. Initial rifting commenced at about 880Ma based on an age of 879±19Ma for the Kafue rhyolites found in the lowest rift sediments (Wardlaw quoted in Hanson et al., 1994) and an age of 877±11Ma for the Nchanga granite (Armstrong et al., 1999) within the pre-Katanga basement. Subsequent sedimentation in late Neoproterozoic to early Palaeozoic foreland basins and orogenic belts was associated with the creation of the Gondwana Supercontinent.

Two (and only two) Cryogenian glaciogenic formations have long been recognized within the Katangan: an older *Grand Conglomerat* and a younger *Petit Conglomerat*. Each glaciogenic formation is overlain by a cap carbonate complex (a typical lithological coupling according to Kennedy et al., 1998). These are respectively, the Kakontwe Limestone Fm and the *Calcaire Rose* Fm. Deposition of the *Grand Conglomerat* occurred after 765Ma and probably before 735Ma (Key et al., 2002). The *Grand Conglomerat* is known throughout the whole Lufilian belt region covering an area of ca. 900x800 km^2 (Fig. 1). The main features observed by previous authors and considered as diagnostic for the glacial origin of the *Grand Conglomerat* are the following: presence of facetted and striated clasts; clast sizes from boulders to granules; massive, matrix-supported conglomerates (diamictites) extremely rich in mud, silty- or sandy-mudstone matrix; sorting absent to very poor, (François, 1973; Dumont and Cahen, 1977); interlayers of varved sediments and outsized dropstone clasts in laminated, fine-grained strata (Binda and Van Eden, 1972; Dumont and Cahen, 1977). A glaciomarine setting was inferred based on interbeds of carbonate rocks, slump beds and turbidites in Zambia (Binda and Van Eden, 1972), calcareous component in muddy matrix of massive conglomerates, and sandstones with calcareous cement in the Democratic Republic of Congo (DRC) (François, 1973). Previous authors have suggested a regional variation in the depositional environments of the *Grand Conglomerat* from deep marine (Binda and Van Eden, 1972), shallow to deep marine (François, 1973) to continental (Andersen and Unrug, 1984).

Two glaciogenic units are also recognized in the other Pan African belts of south-western Africa shown in Fig. 1 (Frimmel et al., 2006) with an older glacial event dated either at between about 751 and 741Ma (Frimmel et al., 1996; Hoffman et al., 1996; Borg et al., 2003), or between about 771Ma and 741Ma (Gaucher et al., 2005) i.e. matching the time constraints for the *Grand Conglomerat*. This sub-continental event is generally correlated with the global Sturtian glaciation (Wendorff et al., 2000; Frimmel et al., 2002; Key et al., 2002; Master et al., 2002; Bodiselitsch et al., 2005). Wingate et al. (2004) and Collins and Pisarevsky(2005) provide palaeomagnetic data that show that NW Zambia/Congo was near the equator at 765-750Ma, i.e. the *Grand Conglomerat* glacial event occurred at low-latitudes. The younger glaciation, including the *Petit Conglomerat*, is generally correlated with the global Marinoan/Varangian glaciation (ca. 640 Ma, Hoffman, 2005, or ca. 620-600 Ma, Master, 1998; Wendorff et al., 2000). A precise dating of cap dolostones from low-latitude Marinoan glacial successions in Namibia, Oman, Newfoundland and South China enabled their correlation and established the timing for termination of this younger snowball earth glaciation at 635Ma (Hoffmann et al., 2004; Condon et al., 2005). Fairchild and Kennedy (2007) provide a comprehensive account of the two Cryogenian glacial events that extended to low latitudes.

The purpose of the present paper is to provide for the first time a description and interpretation of all the sedimentary facies preserved in the *Grand Conglomerat*, regional variations in gross lithology, thickness and stratigraphic relations, in order to present a regional synthesis and ascertain the relative importance of regional topography, tectonics and climate on the glaciation.

2. Stratigraphy of the Katanga Supergroup

Pre-Grand Conglomerat

According to its recently revised stratigraphy (Fig. 2), the Katanga Supergroup is subdivided into the following five groups: Roan (basal group), Nguba, Kundelungu, Fungurume and Plateau (Wendorff, 2003; 2005b; 2005a). In this paper, we replaced the spelling "Guba Group" proposed by Wendorff (2003) with "Nguba Group" to follow a new practice among geologists working in the region (Master et al., 2005; Batumike et al., 2007; Cailteux et al., 2007). The Roan and Nguba groups record two distinct rifting stages resulting from the early Neoproterozoic extension of Rodinia. The Kundelungu, Fungurume and Plateau groups were deposited in the succeeding foreland basins related to Pan African orogenesis that was diachronous from south to north across the Lufilian belt (eventually creating a ‘southern’ Kalahari Craton and a ‘northern’ Congo Craton). The *Grand Conglomerat* Formation is a subdivision of the Nguba Group and records syn-rift glaciation after initial basaltic volcanism. The succeeding *Petit Conglomerat* formed after the first orogenic event to affect the southern part of the Lufilian belt in what is now Zambia.

The Roan Group (Fig. 2), deposited in the first Katangan rift basin (<880Ma), nonconformably overlies variably eroded pre-Katangan basement and forms a continuous transgressive succession from terrigenous clastic sediments (siliciclastic unit, or the Mindola Subgroup) at the base grading upwards into a mixed association of siliciclastic and carbonate strata, the Kitwe Subgroup, succeeded by a carbonate platform sequence, the Bancroft Subgroup, which prograded from the south (Binda, 1994).

Major uplift (≥765 Ma) in the southern part of the Roan rift basin, which is now in Zambia, terminated deposition of the Roan Group platform carbonates and led to the opening of the Nguba rift (Wendorff, 2005a). Syn-rift olistostromes of the Mufulira Formation, derived from uplifted Roan strata, were deposited as products of mass-wasting and sediment gravity-flows at the base of the Mwashya Subgroup (2005b; Wendorff, 2005a). Northward expansion of the Nguba rift, beyond the northern margin of the Roan rift, resulted in progradation of the olistostromes and their nonconformable deposition upon pre-Katangan basement in what is now the fold-thrust belt region in the DRC. The succeeding Mwashya strata are composed of terrigenous siliciclastic rocks, silicified oolitic/pisolitic grainstones, algal dolomites, and ironstones (middle Mwashya), and shales with siltstones grading upwards to black shales deposited under increasingly anoxic conditions (upper Mwashya). Basaltic volcaniclastic rocks and lavas mostly form subordinate interbeds in the Mwashya succession, but are locally significant. For example, a broad basalt lava belt can be traced in a NE direction from eastern Angola across NW Zambia and into southern DRC (Unrug, 1987; Unrug, 1988; Cailteux et al., 1994; Key et al., 2002). In the centre of the basin, the upper boundary of the Mwashya Subgroup is transitional to the *Grand Conglomerat* (Binda and Van Eden, 1972) and defined by the appearance of dropstones in massive or laminated black shales typical for the underlying upper division of Mwashya. Mafic igneous rocks that occur within the Roan, Mwashya and

Grand Conglomerat were interpreted as indicators of rifting continuing throughout the deposition of the Roan and Nguba strata (Kampunzu et al., 2000; Hanson, 2003 – review and discussion). Sedimentary strata that overlie the *Grand Conglomerat* include the Kakontwe Limestone cap carbonate unit as well as banded iron formations; the latter are commonly found in sequences of glacial strata (Kirschvink, 1992).

Post-Grand Conglomerat

Inversion from an extensional to a compressional tectonic regime occurred in the southern Lufilian belt after the deposition of the *Grand Conglomerat* but before the *Petit Conglomerat* was deposited (Wendorff, 2005a). The youngest extension-related igneous rocks occur in the *Grand Conglomerat*. On the other hand, west of the Kafue Anticline in Zambia, the *Petit Conglomerat* rests unconformably on a folded succession of the Roan-Nguba groups. It defines the base of the Kundelungu Group, which is an infill of the first foreland basin (Wendorff, 2005a) composed of marine sandy shales, shales and dolomites, with thick proximal conglomerate complexes occurring in the southern Lufilian belt.

The succeeding Fungurume Group fills the second foreland basin formed in the northern part of the fold-thrust region of the Lufilian belt in the DRC (Wendorff, 2003; Wendorff, 2005a) and contains synorogenic conglomerates and megablocks derived from nappes composed of older Katangan strata uplifted to the south and thrust northwards. The lower boundary is an unconformity above folded Kundelungu Group and the succession evolves from a sedimentary olistostrome to transitional, shallow marine and continental red beds, to shallow marine sequences of siliciclastic and carbonate strata. The degree of deformation gradually decreases between the northern marginal part of the external fold-thrust belt and the succeeding undeformed

Plateau Group further to the north. Continental arkoses and shales of the latter unit were deposited in the youngest foreland basin, extending to the north of the Fungurume Group foreland (Figs. 2&3).

3. Stratigraphy and sedimentary facies of the *Grand Conglomerat* Formation

Eastern area

In the eastern region of the Lufilian belt, in the Mushishima river area west of the Kafue Anticline (Fig. 1, Fig. 3, Section 1), two glaciogenic sediment beds of the *Grand Conglomerat* occur within a conglomerate complex (Garrard, 1965), which unconformably overlies Roan Group siliciclastic strata of the Mindola Subgroup (Wendorff, 2005a). The lower part of the conglomerate complex is correlated with the syn-rift olistostrome succession of the Mufulira Formation (Fig. 3, Section 3). The conglomerate is polymictic, composed of pebbles, cobbles and solitary boulders of Roan-derived dolomite, carbonate pebble and granule conglomerate, quartzite, arkose and siltstone set in a matrix of muddy sandstone cemented by dolomite. The clasts range from rounded to very well rounded. Subangular fragments occur subordinately. The conglomerate is usually matrix-supported, and clast-supported beds are rare. The rock has a massive, disorganised structure. However, dish structures produced by pore fluids escaping out of rapidly deposited sediment occur locally. Indistinct, uneven and discontinuous layering of generally amalgamated beds can also be observed. The textural and structural features suggest that this conglomerate complex was deposited by coarse-grained subaqueous debris flows of high energy and substantial erosional power. The clastic material was derived from an uplifted source area in which Roan carbonate rocks were exposed.

The whole conglomerate complex in the Mushishima River is now interpreted as the proximal facies of a gravelly fan delta, the middle part of which was deposited syn-glacially. A more distal association of a proglacial fan delta, or apron, is represented by an approximately 200 m thick glaciogenic succession at Kansanshi to the west (Fig. 1, locality Ks). It is characterised by coarse glacial rain-out (dropstones) and muddy-silty suspension deposits laid down simultaneously with intermittent sediment-gravity flows ranging from debris flows to turbidites, and associated with subordinate traction currents. The syn-glacial part of the fan delta succession could alternatively be interpreted as grounding-line fans composed of rain-out diamictite associated with gravelly and sandy fan facies deposited seaward of the ice grounding line (Powell, 1990).

Marine sediments of the *Grand Conglomerat* between Chambishi and Mokambo (Fig. 1; Fig. 3, Sections 2 - 4) range from varved laminites with small dropstones (Section 2 - Chambishi) to a massive diamictite (Section 4 - Mokambo). A transitional lower boundary with underlying Mwashya strata occurs at Mufulira and Mokambo, but at Chambishi, the lower boundary is disconformable, with a pronounced hiatus. By comparison with a stratigraphically continuous Mwashya-*Grand Conglomerat* succession at Mufulira (Section 3), the hiatus at Chambishi represents erosion of at least 200 m of the upper and middle divisions of the Mwashya Subgroup.

In borehole section IT 28 at Itawa (Fig. 1; Fig. 3, Section 5) the *Grand Conglomerat* conformably overlies Mwashya dolomitic shale and consists of two dropstone-bearing intervals. The lower one composed of thinly bedded siltstone and very fine-grained sandstone with interbeds of coarse grain-flow sandstone, contains solitary, small angular dropstones of Roan quartzite and dolomite. This interval is overlain by numerous slump beds of mudstone and siltstone, containing rare dropstones, and often evolving to muddy, debris flow beds rich in intrabasinal mudstone clasts. The succeeding second tillite is composed of massive grey and black silty and sandy mudstone rich in subangular to subrounded clasts of sedimentary rocks derived from the Roan-Mwashya succession: siliceous arkose, quartz arenite, grey laminated mudstone, dolomitic sandstone and dolomites ranging in colour from cream to yellowish, orange, pink, light grey and white. The overlying, fining-upwards sequence of conglomerate, sandstone and mudstone is succeeded by a five-metre thick varved interval followed by an association of fine-grained and usually thin turbidites, with rare gravelly debris flow layers and a few slump-deformed beds. Deformational structures are common in this succession and range from loading of dropstones into the underlying beds or laminae, to load structures due to density gradients between sediment layers, to liquefaction of silt or sand.

In the western part of the Bangweulu Block, in the Luapula River section (Fig. 1; Fig. 3, Section 6) a continental association of the *Grand Conglomerat* rests nonconformably on basement granite (Andersen and Unrug, 1984). It consists of massive tillite interbedded with glaciofluvial outwash of sandstone and pebbly sandstone containing angular and subangular pebble-size clasts of vein quartz and granite derived from the bedrock. Cross bedding sandstones indicates palaeocurrent flow towards the southwest and south, shown by azimuths of foresets ranging between 245° and 180°.

NW area

A sequence of variably deformed conglomerates, varved sediments and dropstone-bearing siltstones and shales is preserved in the NW part of the external fold-thrust belt in Zambia between Mwinilunga and Lwaio Mission (Fig. 1 and Fig. 3, Section 7). The conglomerates contain clasts of basement granite and gneiss as well as fragments of Roan rocks. Individual lithologies are up to tens of metres in thickness and the wide range of lithologies indicates that a variety of sedimentary settings was present during the deposition of the *Grand Conglomerat* Formation in this area. The total thickness of the *Grand Conglomerat* in this area is impossible to quantify exactly due to the poor exposure, variable dips of bedding and the absence of boreholes. A figure of 200 m is shown in Fig. 3 but this is almost certainly a minimum thickness. These strata overlie residual clastic sediments derived from *in situ* weathering of immediately underlying mafic volcanic lavas dated at about 765Ma (Key et al., 2002). An age of 735±5Ma was obtained from a volcanic breccia within deformed Nguba strata at Mwinilunga (M in Fig. 1, and Fig. 3, Section 7), but this age is more equivocal in placing a minimum time constraint on the *Grand Conglomerat* due to the strong deformation within this part of the Lufilian belt. However, the dated volcanic rock is spatially associated with carbonate rocks that are not found beneath the *Grand Conglomerat* in the undeformed succession immediately to the west (LM-Lwaio Mission in Fig. 1). These carbonate rocks are reminiscent of cap carbonates, and are here correlated with the Kakontwe Limestone Formation. It is therefore concluded that the *Grand Conglomerat* was deposited prior to 735Ma before overlying Nguba sedimentation and volcanism, but after the 765Ma Mwashya volcanism.

In the NW part of the fold-thrust belt in the DRC, at Lufunfu, the *Grand Conglomerat* is represented by a 950 m thick glaciomarine, massive diamictite (Fig. 3, Section 8) with carbonaceous, slightly calcareous mudstone matrix (François, 1973). A gradual decrease in thickness of the glaciogenic strata towards the south, between Tombolo (Section 9) and Lufunfu (Section 8) is concomitant with a decrease in the dominant clast size from pebble to granule and the wedging out of a conglomerate and sandstone interbed in the same direction. On the other hand, the succeeding cap carbonate – the Kakontwe Limestone – pinches out to the NW (Fig. 3, Sections 8-9), grading laterally into a succession of shale and sandstone. These two simultaneous trends suggest the position of the source of clastic material, and of the marine basin margin, lay to the north.

Northern area

About 150 km north of the fold-thrust belt, in the region of Makonga-Kibambale close to the exposure of the Kibaran basement rocks (Fig. 1; Fig. 3, Sections 10 & 11), the lower boundary of the *Grand Conglomerat* ranges from a pronounced unconformity on the Mwashya Subgroup to a nonconformity on the Kibaran basement (Dumont and Cahen, 1977). Massive diamictite, with facetted and striated clasts up to 30 cm in size of igneous and metamorphic rocks derived from the Kibaran basement to the N and sedimentary rocks from the underlying Mwashya Subgroup, contains interbeds of coarse-grained, cross-bedded, feldspathic wacke with fragments of spilitic lava. Dolerites, basalts, pillow lavas and volcanic breccias intercalated with and overlying the glacial strata (Dumont and Cahen, 1977) have geochemical signatures indicating that volcanicity occurred within an extensional tectonic regime (Kampunzu et al., 2000).

4. Discussion and Conclusions

The described sedimentary facies, stratigraphic relations and igneous rocks locally associated with the *Grand Conglomerat* Formation glaciogenic sediments provide new insights into variations in sedimentary environments, provenance, stratigraphy, tectonic controls on sedimentation and basin evolution during early Cryogenian times. Observations at Mokambo (Fig. 3, Section 4) confirm a transitional lower boundary of the *Grand Conglomerat* into underlying Mwashya fine-grained strata. These older sediments were deposited in a distal, axial or near-axial, part of the marine basin, as previously described at other palaeogeographically similar locations (Binda and Van Eden, 1972). However, laterally, this boundary becomes unconformable towards both the southern and northern margins of the basin (Fig. 1; Fig. 3, Sections 1-2, and 9-11; Fig. 4a) and is overlain by glaciomarine deposits in the south and glaciofluvial in the north.

In the south, the glacial strata at Chambishi (Fig. 3, Section 2) comprise varved sediments with fine dropstones overlying a pronounced erosional unconformity. The unconformity-related hiatus increases towards the SW, and at Mushishima (Fig. 3, Section 1), the *Grand Conglomerat* occurs within a thick wedge of proximal, non-glacial, fan delta conglomerate (Fig. 4a), which rests upon Lower Roan siliciclastic strata (Mindola Subgroup). The fan delta conglomerates contain a variety of clasts including the pebbles of dolomite that are lithologically identical to dolomites found in the Roan basin south of the Kafue Anticline. Therefore, it is now inferred that the conglomerates were derived from a strongly uplifted source area in the south. At Kansanshi to the west, glaciogenic interlayers in a distal, fan delta facies association (Fig. 1) contain fall-out clasts (dropstones) of Mwashya lithologies that also occur in the southern part of the Katangan region. In the basin-centre succession at Itawa (Fig. 3, Section. 5), there are dropstones of Roan quartzite and dolomite, and of various Mwashya lithologies. Both clast types are also derived from the south.

In the northernmost part of the Lufilian belt, which extends north of the fold-thrust belt and remained essentially undeformed during the Lufilian orogeny (Fig. 1), the *Grand Conglomerat* rests nonconformably on pre-Katangan basement or disconformably overlies the Mwashya Subgroup (Fig. 1, Fig. 3, Sections 10, 11 and Fig. 4b). Clasts of Mwashya provenance prevail (Dumont and Cahen, 1977), which implies a pronounced hiatus due to glacial erosion as most, or all, of the Mwashya succession has been removed. Similarly deep glacial erosion, followed by very high rates of syn-*Grand Conglomerat* subsidence, occurred locally in the NW part of the fold-thrust belt, as illustrated by Tombolo section in Figs. 3 and 4b. There, where the *Grand Conglomerat* rests nonconformably on Kibaran basement rocks, the massive glacial tillite is interlayered with cross-bedded, pebbly, fluvial sandstone beds (Dumont and Cahen, 1977). In the Bangweulu Block area further SE, in the Luapula River Valley in Zambia (Fig. 1, Fig. 3, Section 6 and Fig. 4a), the *Grand Conglomerat* is an association of glacial tills and glaciofluvial strata nonconformably overlying pre-Katangan basement rocks and contains angular basement-derived clasts. These occurrences testify to the continental nature of glaciation in parts of the northernmost sector of the Katangan region extending well beyond the external fold-thrust belt (Fig. 3, Sections 6, 10 & 11), and to a local derivation of the coarse clastic components.

Further to the south, in the western part of the fold-thrust belt, a pronounced unconformity at the base of the *Grand Conglomerat* at Tombolo (Fig. 3, Section 9) evolves into a conformable boundary towards the central/distal part of the marine basin at Lufunfu (Fig. 3, Section 8; Fig. 4b). Clasts derived from the Kibaran basement to the north and from Mwashya lithologies occur in marine glaciogenic sediments in the north and centre of the fold-thrust belt in the DRC (François, 1973; Dumont and Cahen, 1977; Cailteux, 1990). Lateral trends of the marine facies in the northern part of the fold-thrust belt (François, 1973) and of the glaciofluvial sediments in the Bangweulu Block area (Andersen and Unrug, 1984) support the southwest & south-oriented sediment supply system and palaeocurrent directions reported in this paper.

The above observations imply that both the southern and northern margins of the Nguba basin acted as a source zone for the material supplied to the adjacent part of the depository during the *Grand Conglomerat* glaciation. The southern source was a strongly uplifted region on which pronounced unconformities developed and the deglaciation sequences include high energy, proximal conglomerates of proglacial fan deltas (Fig. 4a). At the northern margin, the continental glaciogenic sediments grade southward/basinward into glaciomarine melt-out deposits, which are associated with, and overlain by proximal sandstone interbeds, probably representing beach or shallow marine arenites. These proximal clastic facies evolve further southward to a distal cap carbonate unit of the Kakontwe Limestone, a pattern suggesting that the proximal marine strata originated in a gently sloping, graded shelf during the syn- and immediately post-glacial period (Fig. 4b). The regional unconformities at the base of the glaciomarine *Grand Conglomerat* facies correlatable between northern and southern margins of the basin (Figs. 2, 3 and 4) suggest regional, glaciation-induced, eustatic sea-level fall and subsequent glacial erosion, followed by eustatic sea-level rise with associated deposition of the glaciomarine deglaciation sequences.

The Kakontwe Limestone cap carbonate is confined to distal parts of the marine basin (Fig. 3, Sections 3, 4, 7, 8; Fig. 4) and passes laterally into terrigenous sediments coarsening towards the basin margins. Its absence in the proximal parts of the depository is here considered to reflect high sediment flux comprising glaciogenic debris derived from deglaciated land, which 'diluted' simultaneously ongoing carbonate sedimentation.

The regional tectonostratigraphic relations and palaeotopography interpreted in this paper point to a simultaneous glaciation of both low (northern rift margin evolving to graded shelf – Fig. 4b) and high (strongly uplifted southern margin – Fig. 4a) relief. Such palaeotopographic contrast between the basin margins implies that the *Grand Conglomerat* glaciation was independent from ongoing rifting of the Nguba basin. This is contrary to the scenario suggested by Porada and Berhorst (2000) who envisaged that uplift of the Katangan rift shoulders was responsible for the establishment of the glacial conditions.

The symmetry of glaciation in the asymmetrical Nguba rift indicates that non-topographic controls triggered the development of glacial conditions. These observations, and the results of Wingate et al. (2004) and Collins and Pisarevsky (2005), who indicate that the NW Zambia/S Congo region was located at the Equator between about 800 and 750Ma, are consistent with the 'Snowball Earth' hypothesis (Hoffman, 2005). However, the interlayering of glacial and non-glacial sediments is similar to Phanerozoic glaciogenic sequences and the presence of water-borne continental sediments as well as floating glacier-derived fall-out sediments in the *Grand Conglomerat* would mitigate against the 'extreme frigidity' of a 'Snowball Earth' (Fairchild and Kennedy, 2007). Thus, the following lithological and sedimentological characteristics of the *Grand Conglomerat* indicate its sediments were deposited during a complex multistage event (with glacial and inter-glacial stages):

(i) syn-glacial, fan delta successions, including gravity flow deposits and complexes of deglaciation-related fall-out facies alternating with massive dropstone-devoid mudstones of glacial maxima (e.g. at Kansanshi);

(ii) intervals containing lenticular laminations with lenticles defined by isolated current ripple marks composed of fine-grained sandstone, interpreted here as traction current deposits, possibly contourites (e.g. Itawa);

(iii) individual deglaciation stages marked by vertical successions of separate marine tillites (eg. Itawa), in more proximal settings separated by interglacial marine sandstone complexes (e.g. at Tombolo)

(iv) the presence of laminites reminiscent of seasonal varved sediments (possibly bi-annual), especially at Itawa where they occur in the upper part of the glaciogenic suite.

It is therefore suggested that these features imply prolonged glaciation with interglacial periods and gradual deglaciation associated with redeposition of interglacial and post-glacial debris accumulated in the source areas, into the adjacent marine depository. The observed sedimentary facies may indicate a lack of permanent sea ice cover at certain periods during deposition of the Grand Conglomerat sediments. It may also suggest that such a glaciation would not have undergone rapid change to a greenhouse environment.

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References

Andersen, L.S., Unrug, R., 1984. Geodynamic evolution of the Bangweulu Block, Northern Zambia. Precambrian Research 25, 187-212.

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. In: Robb, L.J., J., C.Sutton, S.J. (Eds.), Recent Advances in the Geology and Mineralization of the Central African Copperbelt. Journal of African Earth Sciences, 32-40.

Armstrong, R.A., Robb, L.J., Master, S., Kruger, F.J., Mumba, P.A.C.C., 1999. New U-Pb age constraints on the Katangan Sequence, Central African Copperbelt. Journal of African Earth Sciences, Special Abstracts Issue, GSA 11: Earth Resources for Africa 28, 6-7.

Batumike, M.J., Cailteux, J.L.H., Kampunzu, A.B., 2007. Lithostratigraphy, basin development, base metal deposits, and regional correlations of the Neoproterozoic Nguba and Kundelungu rock successions, central African Copperbelt. Gondwana Research 11, 432-447.

Binda, P.L., 1994. Stratigraphy of Zambian Copperbelt orebodies. Journal of African Earth Sciences 19, 251-264.

Binda, P.L., Van Eden, J.G., 1972. Sedimentological evidence for the origin of the Precambrian Great Conglomerate (Kundelungu Tillite), Zambia. Palaeogeography, Palaeoclimatology, Palaeoecology 12, 151-168.

Bodiselitsch, B., Koeberl, C., Master, S., Reimold, W.U., 2005. Estimating duration and intensity of Neoproterozoic Snowball Glaciations from Ir anomalies. Science 308, 239-242.

Borg, G., Kaerner, K., Buxton, M., Armstrong, R., van-der-Merwe, S.W., 2003. Geology of the Skorpion supergene zinc deposit, southern Namibia. In: Sangster, D.F. (Ed.), Nonsulfide zinc deposits; a new look. Economic Geology and the Bulletin of the Society of Economic Geologists 98, 749-771.

Cailteux, J., 1990. La tectonique intra-katanguienne dans la région Nord-Ouest de l'Arc Lufilien (Shaba, Rép. du Zaïre). Annales de la Société géologique de Belgique 113, 199-215.

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 (Zaire) and Zambia, in the central African copper-cobalt metallogenic province. Journal of African Earth Sciences 19, 265-278.

Cailteux, J.L.H., Kampunzu, A.B., Lerouge, C., 2007. The Neoproterozoic Mwashya–Kansuki sedimentary rock succession in the central African Copperbelt, its Cu–Co mineralisation, and regional correlations. Gondwana Research 11, 414-431.

Collins, A.S., Pisarevsky, S.A., 2005. Amalgamating eastern Gondwana: the evolution of the circum-Indian orogens. Earth Science Reviews 71, 229-270.

Condon, D., Zhu, M., Bowring, S., Wang, W., Yang, A., Jin, Y., 2005. U-Pb ages from the neoproterozoic Doushantuo Formation, China. Science 308, 95-98.

Dumont, P., Cahen, L., 1977. Les complexes conglomeratiques de la bordure sud-orientale de la Chaine Kibarienne et leurs relations avec les couches Katangiennes de l'Arc Lufilienne, Rapport Annuelle 1977. Museé royal de l'Afrique centrale, Départment de Géologie et Minéralogie, Tervuren, Belgique, 111-135.

Fairchild, I.J., Kennedy, M.J., 2007. Neoproterozoic glaciation in the Earh System. Journal of the Geological Society of London 164, 895-921.

François, A., 1973. L'extremité Occidentale de l'Arc Cuprfère Shabien, Etudé Géologique. Gécamines, Lubumbashi, p. 65.

François, A., Cailteux, J., 1981. La couverture Katangienne entre les socles de Zilo et de la Kabompo, Républiqué du Zaïre, région de Kolwezi. Annales Sciences Géologiques, 87. Museé royal de l'Afrique Centrale, Tervuren, Belgique, p. 50.

Frimmel, H.E., Fölling, P.G., Eriksson, P.G., 2002. Neoproterozoic tectonic and climatic evolution recorded in the Gariep belt, Namibia and South Africa. Basin Research 14, 55-67.

Frimmel, H.E., Klötzli, U.S., Siegfried, P.R., 1996. New Pb-Pb single zircon age constraints on the timing of neoproterozoic glaciation and continental break-up in Namibia. Journal of Geology 104, 459-469.

Frimmel, H.E., Tack, L., Basei, M.S., Nutman, A.P., Boven, A., 2006. Provenance and chemostratigraphy of the Neoproterozoic West Congolian Group in the Democratic Republic of Congo. Journal of African Earth Sciences 46, 221-239.

Garrard, P., 1965. Geological Map of the Chingola area 1:100.000. Geological Survey of Zambia, Lusaka.

Gaucher, C., Frimmel, H.E., Germs, G.J.B., 2005. Organic-walled microfossils and biostratigraphy of the upper Port Nolloth Group (Namibia): implications for latest Neoproterozoic glaciations. Geological Magazine 145, 539-559.

Hanson, R.E., 2003. Proterozoic geochronology and tectonic evolution of southern Africa. In: Yoshida, M., Windley, B.F.Dasgupta, S. (Eds.), Proterozoic East Gondwana: Supercontinent Assembly and Breakup. Special Publication 206. Geological Society of London, 427-463.

Hanson, R.E., Wilson, T.J., Munyanyiwa, H., 1994. Geologic evolution of the Neoproterozoic Zambezi Orogenic Belt in Zambia. Journal of African Earth Sciences 18, 135-150.

Hoffman, P.F., 2005. On Cryogenian (Neoproterozoic) ice sheet dynamics and the limitations of the glacial sedimentary record. South African Journal of Geology 108, 557-577.

Hoffman, P.F., Hawkins, D.P., Isachsen, C.E., Bowring, S.A., 1996. Precise U-Pb zircon ages for early Damaran magmatism in the Summas Mountains and Welwitschia Inlier, northern Damara Belt, Namibia. Communications - Geological Survey of Namibia 11, 47-52.

Hoffmann, K.-H., Condon, D.J., Bowring, S.A., Crowley, J.L., 2004. U-Pb zircon date from the Neoproterozoic Ghaub Formation, Namibia: constraints on Marinoan glaciation. Geology 31, 817-820.

Kampunzu, A.B., Tembo, F., Matheis, G., Kapenda, D., Huntsman-Mapila, P., 2000. Geochemistry and tectonic setting of mafic igneous units in the

Neoproterozoic Katangan basin, Central Africa: implications for Rodinia breakup. Gondwana Research 3, 125-153.

Kennedy, M.J., Runnegar, B., Prave, A.R., Hoffman, K.H., Arthur, M.A., 1998. Two or four Neoproterozoic glaciations? Geology 26, 1059-1063.

Key, R.M., Liyungu, A.K., Njamu, F.M., Somwe, V., Banda, J., Mosley, P.M., Armstrong, R.A., 2002. The western end of the Lufilian arc in NW Zambia and its potential for copper deposits. Journal of African Earth Sciences 33, 503-528.

Kirschvink, J.L., 1992. Late Proterozoic low-latitude glaciation: the snowball Earth. In: Schopf, J.W.Klein, C. (Eds.), The Proterozoic Biosphere. Cambridge University Press, Cambridge, 51-52.

Master, S., 1998. New developments in uderstanding the origin of the Central African Copperbelt. Abstracts, Mineral Deposits Studies Group Annual Meeting (unpaginated), University of Greenwich, Chatham Maritime, UK, 2 pp.

Master, S., Rainaud, C., Armstrong, R.A., Phillips, D., Robb, L.J., 2002. Contributions to the geology and mineralization of the Central African Copperbelt: II. Neoproterozoic deposition of the Katanga Supergroup with implications for regional and global correlations. Geocongress-IAGOD Joint Meeting, Extended Abstracts on CD-ROM (unpaginated), Windhoek, Namibia, 4.

Master, S., Rainaud, C., Armstrong, R.A., Phillips, D., Robb, L.J., 2005. Provenance ages of the Neoproterozoic Katanga Supergroup (Central African Copperbelt), with implications for basin evolution. Journal of African Earth Sciences 42, 41-60.

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. Journal of African Earth Sciences 30, 727-771.

Powell, R.D., 1990. Glacimarine processes at grounding-line fans and their growth to ice-contact deltas. In: Dowdeswell, J.A. & Scourse, J.D. (Eds.), Glacimarine enviromments: processes and sediments. Geological Society of London Special Publication 53, 53-73.

Unrug, R., 1987. Geodynamic evolution of the Lufilian arc and the Kundelungu aulacogen: Angola, Zambia and Zaire. In: Matheis, G.Schandelmeier, H. (Eds.), Current Research in African Earth Sciences; 14th Colloquium of African Geology, Extended Abstracts. Balkema, Rotterdam, 117-120.

Unrug, R., 1988. Mineralization controls and source of metals in the Lufilian Fold Belt, Shaba (Zaire), Zambia and Angola. Economic Geology 83, 1247-1258.

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. South African Journal of Geology 106, 17-34.

Wendorff, M., 2005a. Evolution of Neoproterozoic-Lower Palaeozoic Lufilian arc, Central Africa: A new model based on syntectonic conglomerates. Journal of the Geological Society of London 162, 5-8.

Wendorff, M., 2005b. Sedimentary genesis and lithostratigraphy of Neoproterozoic megabreccia from Mufulira, Copperbelt of Zambia. Journal of African Earth Sciences 42, 61-81.

Wendorff, M., Kampunzu, A.B., Cailteux, J., Binda, P.L., 2000. Tectonosedimentary evolution of the Central African Copperbelt. 31 International Geological

Congress, Neoproterozoic Symposium F-7, Extended Abstracts on CD ROM (unpaginated), Rio de Janeiro, Brazil, 1-4.

Wingate, M.T., Pisarevsky, S.A., De Waele, B., 2004. Paleomagnetism of the 765 Ma Luakela volcanics in NW Zambia and implications for Neoproterozoic positions of the Congo Craton. Eos Trans. AGU, 85 (47), Fall Meeting Supplement Abstract U32A-03.