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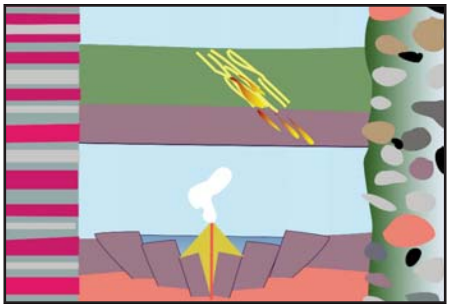

Comparative Stratigraphic and Geochronological Evolution of the Northern Damara Supergroup in Namibia and the Katanga Supergroup in the Lufilian Arc of Central Africa

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SUMMARY

The Damara Supergroup in Namibia and the Katanga Supergroup in the Central African Copperbelt (some 1000 km apart) are characterized by rock successions indicative of almost coeval orogenic evolution through phases of intracontinental rifting, spreading, continental rupture, subduction, ocean closure and continental collision in what appears to have been a single, elongate orogenic belt. Rifting began at about 880 Ma and lasted until about 800 or 756 Ma. Post-rift thermal sag and marine transgression produced the first correlatable stratigraphic units, the argillaceous Beesvlakte and Ore Shale Formations, in northern, carbonate-dominated platformal successions on the Damaran Northern Platform and the Katangan Lufilian Arc or Fold Belt, respectively. Sturtian (~735 Ma) and Marinoan (635 Ma) glacial units are common to both successions as well as syntectonic molasse sequences (~595–550 Ma). Continental collision occurred at about 542 Ma and the post-tectonic peak of regional metamorphism was at about 535–530 Ma. Mineral ages record cooling to about 460 Ma. The extensive occurrence of stratabound, but not stratiform, copper mineralization, evaporitic minerals, salt and thrust tectonics, syntectonic breccias, and intense alteration in the Lufilian Arc have no significant equivalents in the Northern Platform. However, the Beesvlakte Formation has both concordant and strongly discordant styles of copper mineralization and the mode of occurrence of mineralization in the Copperbelt can be a guide to exploration in Namibia.

SOMMAIRE

Le Supergroupe de Damara en Namibie et le Supergroupe de Katanga de la bande cuprifère d'Afrique centrale (distant de 1 000 km) sont caractérisés par des successions de roches montrant une évolution orogénique presque contemporaines dans leurs phases de distension intracontinentale, d'expansion, de rupture continentale, de subduction, de fermeture océanique et de collision continentale, dans ce qui semble avoir été une seule et même bande orogénique étroite. La distension a débutée il y a environ 880 Ma et s'est prolongé jusqu'à 800 Ma ou 756 Ma. Le fléchissement thermique post-distension et la transgression marine ont donné les premières unités stratigraphiques corrélables, soit la Formation argileuse de Beesvlakte et la Formation de Ore Shale, de la portion nord des successions de plateforme principalement carbonatées sur la Plateforme nord de Damaran et de l'Arc ou de la bande plissée de Katangan Lufilian respectivement. Les unités glaciaires de Sturtian (~735 Ma) et de Marinoan (635 Ma) sont communes aux deux successions, tout comme les séquences de molasses syntectoniques (~595–550 Ma). La collision continentale s'est produite il y a environ 542 Ma et le pic post-tectonique de métamorphisme régional a eu lieu il y a environ 535 à 530 Ma. Selon les datations minérales, le refroidissement s'est produit il y a environ 460 Ma. La prépondérance du contexte stratoïde plutôt que stratiforme des minéralisations de cuivre, des minéraux d'évaporites, de sel et de tectonique de compression, de brèches syntectoniques, et d'altération intense dans l'Arc de Lufilian, n'a pas d'équivalent dans la plateforme du nord. Cependant, la Formation de Beesvlakte présente des minéralisations de cuivre qui sont ou concordantes, ou fortement discordantes, et le mode d'occurrence de la minéralisation dans le bande cuprifère peut servir de guide à l'exploration en Namibie.

INTRODUCTION

A correlation of the Damara Supergroup of Namibia, particularly the Otavi Group of the Northern Plat-

Geoscience Canada, v. 40, http://dx.doi.org/10.12789/geocanj.2013.40.007

form of the Damara Orogen, with the Katanga Supergroup of the Lufilian Arc or Fold Belt in Zambia and the Democratic Republic of Congo (DRC) (Figs. 1, 2), i.e. the Central African Copperbelt, has long been accepted on the basis of broadly similar rock types, platform-like tectonic settings and geochronological data (Haughton 1963; Cahen and Snelling 1966; Cahen et al. 1984). The two regions underwent approximately coeval phases of rifting, ocean opening and closure, subduction and continental collision. Recent geochronological data are worth investigating further in order to tighten this correlation and to highlight the potential for Copperbelt-type mineralization in Namibia and for Damaran-type lead-zinc mineralization in the Katanga Supergroup.

The recognition of two 'Snowball Earth' glacial units, the Chuos and Ghaub Formations (~735 Ma and 635 Ma, respectively), in the Damara Supergroup (Hoffmann and Prave 1996; Hoffman et al. 1998a) enable a direct correlation with the Grand and Petit Conglomérat of the Katanga Supergroup (Master and Wendorff 2011) to be made. The individual cap carbonates are similar: grey and laminated above the Chuos Formation and Grand Conglomérat, and tan or pink above the Ghaub Formation and Petit Conglomérat. Dates for many stages in the evolutionary history of these two regions are almost identical.

This paper briefly compares the lithostratigraphy (Table 1) and the chronology of sedimentary, structural and metamorphic evolution (Tables 2-5) in these two major regional successions. Supporting information is gleaned from the adjoining Kaoko, central Damara, and Zambezi Belts, all of which evolved coevally with their corresponding platform facies. A few relevant dates from the Nama foreland succession are given.

Exposures of Neoproterozoic rocks in the Aha Hills along the northern Namibia/Botswana border (Miller and Schalk 1980), in the Tsodilo Hills of northwest Botswana (Haughton 1969) and within the Zambezi supracrustal sequence to the south and west of Lusaka (Johnson et al. 2007; Munyanyiwa and Hanson 1988) are too sporadic and meagre to allow the construction of detailed stratigraphic sections but they do document a near continuous extent of Damaran/Katangan geology across the 1000 km 'gap' between the main exposures in Namibia and DRC/Zambia.

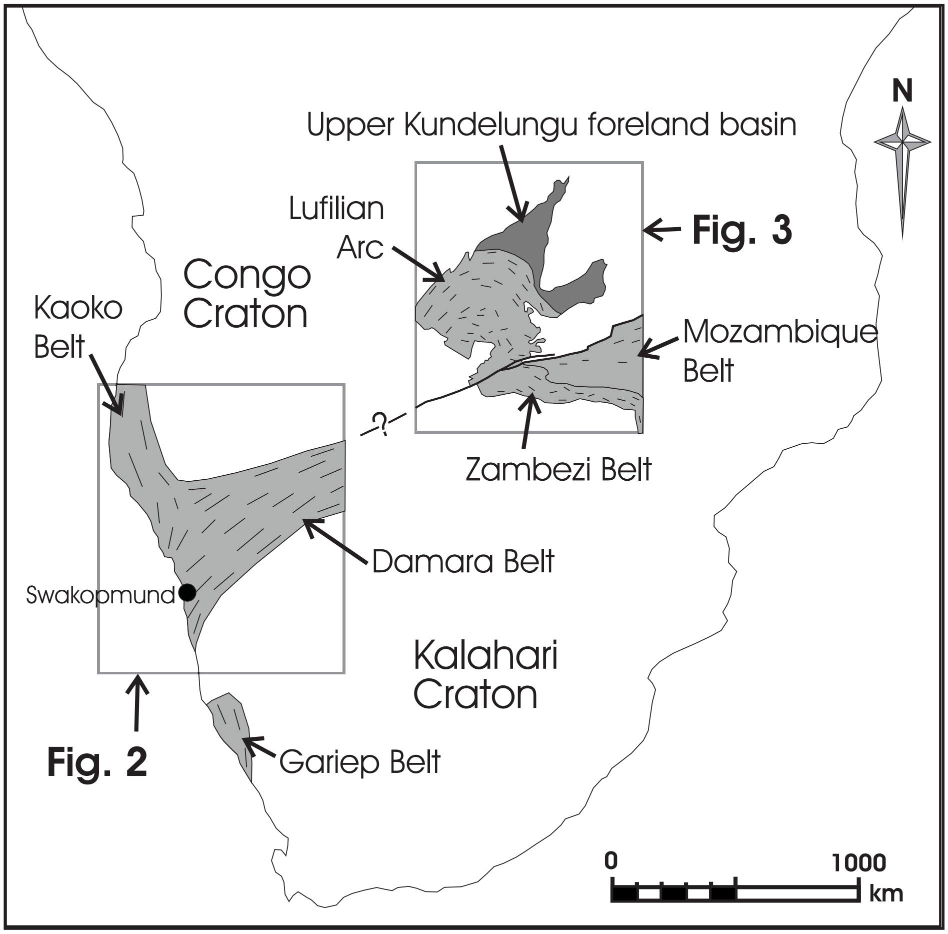

Figure 1. Relative locations of the Pan-African Damara Orogen and Lufilian Fold Belt in southern Africa (modified after Miller and Schalk 1980; Kampunzu and Cailteux 1999; Porada and Berhorst 2000).

GENERAL STRATIGRAPHY AND STRUCTURE

Damara Orogen

Namibia's Damara Orogen, consisting of three arms meeting at a triple junction in the region of Swakopmund (Miller, 1983a, 2008; Miller et al. 2009a, b; Frimmel 2009; Fig. 1), evolved through phases of intracontinental rifting, spreading, compression and continental collision. Appropriate sedimentary rock facies were deposited during each of these stages in the northeast-trending Damara Belt (Martin 1965; Barnes and Sawyer 1980; Miller 1983a, 2008; Miller et al. 2009a, b; Hoffman and Halverson 2008), the north–south-trending Kaoko Belt (Guj 1970; Goscombe et al. 2003a, b; 2005a, b; Miller 2008; Miller et al. 2009a, b) and its southern equivalent, the Gariep Belt (Frimmel 2008). The evolutionary relationships of these three belts to each other are comprehensively covered by Frimmel and Miller (2009a, b), Frimmel et al. (2009), Germs et al. (2009), Miller and Frimmel (2009), Miller et al. (2009a, b) and Will et al. (2009). The Damara and Kaoko Belts are divided into contrasting tectonostratigraphic zones, but the Northern Platform is common to both (Fig. 2). Hedberg (1979), Hoffman and Halverson (2008) and Miller (2008) provide detail of Northern Platform stratigraphy; however, the reader needs to be aware that Hedberg's (1979) Abenab Subgroup in the western parts of the platform is the present Ombombo Subgroup (Table 1). Only the 'transition beds' in the Otavi Mountainland are included in the Ombombo Subgroup and Hed-

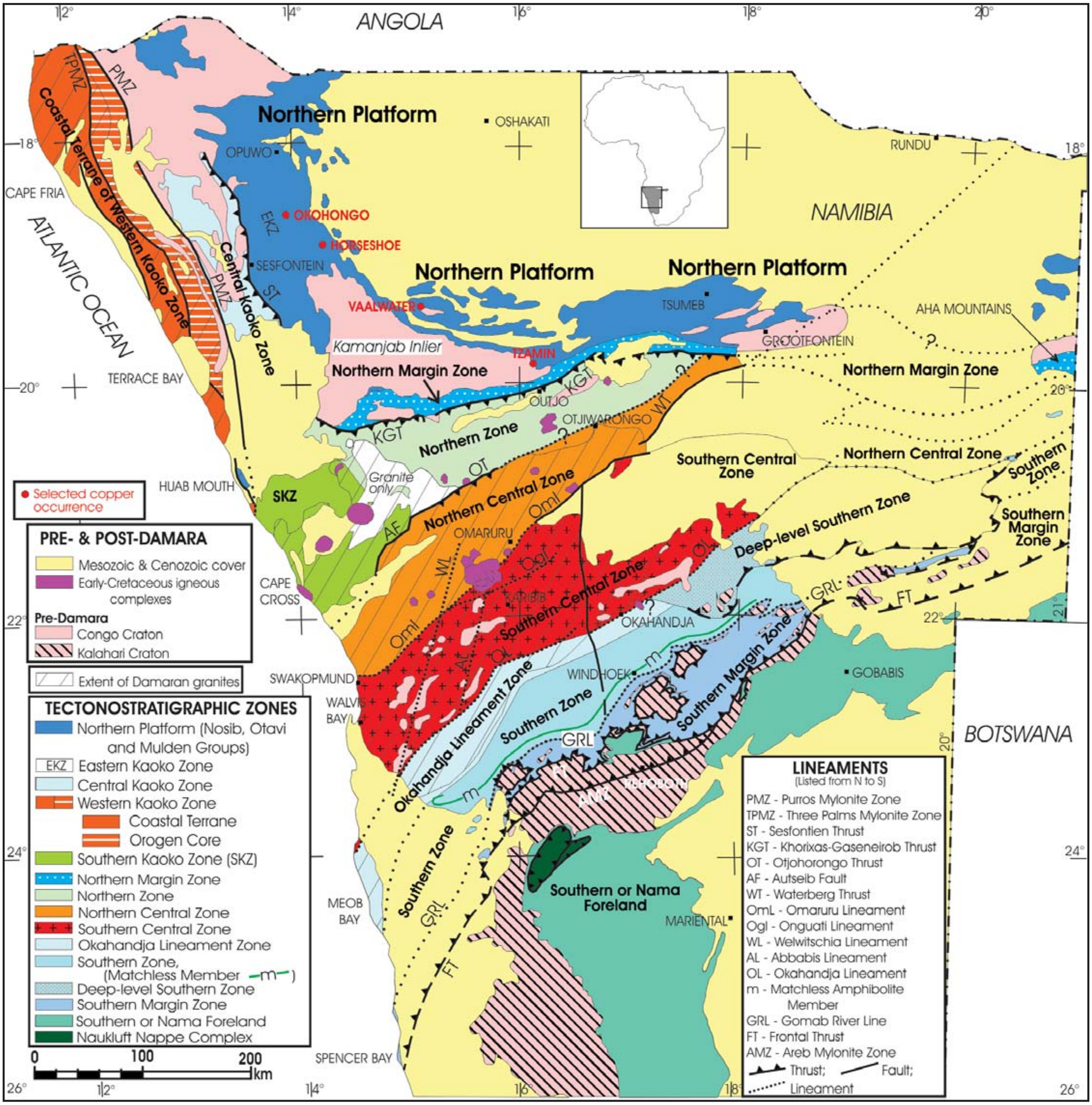

Figure 2. Tectonostratigraphic zones of the Damara Orogen (modified and simplified after Miller 2008). The Eastern Kaoko Zone (EKZ) is stratigraphically and structurally continuous with the western edge of the Northern Platform and differs only from the latter in the greater tightness of its folds. The Damaran sequence is continuous beneath the Mesozoic to Cenozoic cover on the Northern Platform.

berg's (1979) Abenab Subgroup in this eastern region is equivalent to the Abenab Subgroup in today's classification (Miller 2008).

Intracontinental Rifting

The Nosib Group (~900 – 756 Ma), the rift-phase succession, consists mainly of pale pink, hematitic, feldspathic to arkosic, fluviatile quartzites and minor conglomerates that are up to 6 km in thickness. These beds accumulated in two, parallel, northeast-trending rifts in the central part of the Damara Belt, and as sheet sands or wedge-shaped deposits, some with rapid thickness variations, in numerous half-grabens between and marginal to the rifts (Miller 2008). The Nosib succession in the Northern Platform fines upwards and becomes highly ferrugi-

Table 1. Proposed stratigraphic correlation of the Damara Supergroup in the Northern Platform and Northern Margin Zone of the Damara Orogen of Namibia with the Katanga Supergroup in the Central African Copperbelt of Zambia and the Democratic Republic of Congo. Damaran nomenclature is from Miller (1983a, 2008), Hoffmann and Prave (1996), and Hoffman and Halverson (2008). Katangan nomenclature is from Porada and Berhorst (2000), Cailteux et al. (2007), Batumika et al. (2007), Kampunzu et al. (2009) and in part from Selley et al. (2005).

Namibia				**Zambia and/or *Democratic Republic of Congo (DRC)***			
SG	**Group**	**Subgroup; Age**	**Formation**	**Formation**	**Subgroup; Age**	**Group**	**SG**
DAMARA	MULDEN	550? Ma	Owambo		***Biano*** ~550 Ma	*KUNDULUNGU*	*KATANGA*
			Kombat	*Sampwe*	***Ngule*** 595 Ma		
			Tschudi	*Kiubo*			
		~595 Ma		*Mongwe*			
	OTAVI	600? Ma **Tsumeb**	Hüttenberg	*Lubudi*	***Gombela***		
			Elandshoek	*Kanianga*			
		~609 Ma	Maieberg	*Lusele*			
		635 Ma	Ghaub	*Kyandamu (Petit Congl)*			
		Abenab	Auros/ Ombaatjie	*Monwezi*	***Bunkeya***	*NGUBA*	
				Katete			
			Gauss/ Gruis	*Kipushi*	***Muombe*** 735 Ma		
				Kakontwe			
			Berg Aukas /Rasthof	*Kaponda*			
		~735 Ma	Chuos	*Mwale (Gr. Congl)*			
		746 Ma 759 Ma **Ombombo**	Okakuyu	*Kanzadi* *Kafubu* *Kamoya*	**Mwashia / *Mwashya*** 765 Ma	ROAN / *ROAN*	
			Devede + U Naauwpoort	Bancroft / *Kansuki, Mofya-R3.3* Kanwangungu / *R3.2*	**Kirilabombwe/ *Dipeta*** (evaporites)		
				Kibalongo / *RGS-R3.1*			
			Beesvlakte + U Naauwpoort	Chingola / *Kambove*	**Kitwe/ *Mines - R2*** (evaporites)		
				Pelito-arkosic / *U Dolomitic shales*			
				Ore Shale / *L Dolomitic shales Kamoto*			
	NOSIB	757 Ma	Askevold/ L Naauwpoort		?804 Ma		
			Nabis	Mutonda	**Mindola/ *RAT1 - R1*** (fluvial) (evaporites) 880 Ma		
				Kafufya			
		900? Ma		Chimfunsi			

▩ Rift units ■ Glacial units ▨ Cap carbonate ░ Molasse nous (Hedberg 1979). Thick, local peralkaline ignimbrites (Naauwpoort Formation), some with associated subvolcanic alkaline intrusions, occur at the top of the group just south of the southern edge of the Northern Margin Zone (Frets 1969; Miller 1980, 1983a) (Fig. 2; Table 2). Coeval, highly epidotized leucitites host copper mineralization in the Askevold Formation (Miller 1983a; Kombat Suid formation of Söhnge 1957). Upper Nosib sedimentary rocks locally contain volcanic fragments (Hedberg 1979). The Nosib Group reaches 1200 m in thickness in the platformal Otavi Mountainland and 1500 m in the western parts of the Northern Platform (Hedberg 1979), where the Nosib also displays extensive potassic alteration (Jennings and Bell 2011). Evaporitic rocks occur at the top of the succession in the southern rift of the central Damara Belt (Behr et al. 1983a, b) and are believed to have been present near the base of the thick sedimentary fill of the northern rift (Weber et al. 1983; Miller 2008). Hoffman and Halverson (2008) report a few pseudomorphs after evaporitic minerals at the top of the Nosib in the western part of the Northern Platform.

Evolution from Rifting to Spreading

During slow evolution from rifting to spreading and final continental rupture in the Damara and Kaoko Belts, the siliciclastic-dominated Swakop Group was deposited in the central part of the orogen and the carbonate-dominated Otavi Group was deposited on the Northern Platform and its deeper-water marginal regions, the Eastern Kaoko Zone and the Northern Margin Zone (Fig. 2). Cyclical deposition typifies most units of the Otavi Group in the western part of the Northern Platform (Hoffman and Halverson 2008).

The Ombombo Subgroup (Hoffmann and Prave 1996), which is divided into the Beesvlakte, Devede and Okakuyu Formations (Tables 1, 2), coarsens upwards but fines northwards in concert with a northward deepening of western parts of the Northern Platform 'lagoon' (Hoffman and Halverson 2008; Hoffman 2011). The contact of the Beesvlakte Formation with underlying rocks of the Nosib Group appears to be an abrupt flooding surface (Hoffman and Halverson 2008). The base of the formation consists of recessive purplish phyllite and siltstone and channels of pebbly sandstone. Layers of laminated pink dolomite increase in number up towards a middle marker unit of tectonized, weather-resistant, sericitic dolomite displaying light and dark coloured cherty beds. This unit is capped by microbial laminite that has an exposure surface at the top. The dolomite passes into black limestone northwards. Above this are highly tectonized, recessive 'ribbonites', marly rhythmites and sericitic dolomite that grade upwards into the basal Devede Formation (Hoffman and Halverson 2008). The Devede Formation, consisting of phyllite and minor carbonate interbeds, is widespread. It varies in colour from dark grey (mainly) to light grey or pinkish and is described by Hedberg (1979) from several localities north of the Kamanjab Inlier, where thicknesses vary but reach 300 m in the Opuwo area. Martin (1965) assigned it to the upper Nosib Group and Hedberg (1979) included it in some of his descriptions of the Nosib succession, although he generally regarded it either as a transition sequence or the basal part of what was called the Abenab Subgroup at the time (now Ombombo Subgroup).

The Beesvlakte phyllites near the western margin of the Northern Platform and along the northern edge of the Kamanjab Inlier host disseminated, discordant and possibly concordant copper mineralization (Schneider and Seeger 1992). The Beesvlakte Formation has been divided informally into a thin, basal Omivero formation and lower and upper Omao formation by Jennings and Bell (2011) who point out that most of the approximately 200 copper showing in the Eastern Kaoko Zone and along the northern edge of the Kamanjab Inlier occur in the Omivero and lower Omao formations. The Beesvlakte Formation is usually recessive (Hoffman and Halverson 2008) and is commonly covered by scree, alluvium or thin calcrete (Jennings and Bell 2011).

The Devede Formation is made up of stacked cycles of northward-fining siliciclastic rocks, grainstones and pinkish stromatolitic carbonates (Hoffman and Halverson 2008). There are a few interbeds of pyroclastic rocks related to the final pulses of Naauwpoort volcanism. The overlying Okakuyu Formation consists of cycles of deltaic clastic rocks that coarsen upwards but fine and thicken northwards. Phyllites in the Okakuyu Formation are purplish in colour, and sandstones reddish brown; a stromatolitic dolomite featuring patches of oolite forms the top of the formation (Hoffman and Halverson 2008). The Ombombo Subgroup includes the heterolithic siliciclastic and carbonate 'Transition Beds' (Söhnge 1957) in the Otavi Mountainland in the Tsumeb area (Miller 2008).

The glaciogenic, Sturtian-age Chuos Formation at the base of the Abenab Subgroup (Table 3) contains mainly basement-derived clasts, although some clasts are from the immediately underlying Nosib and Ombombo rocks. Associated oxide iron formation (Martin 1965; Roesener and Schreuder 1992) is a distinguishing feature (Miller 2008). The dark grey, laminated Rasthof Formation in the west (Hedberg 1979; Hoffman et al. 1998a, b; Hoffman and Schrag 2002; Hoffman and Halverson 2008) and the laterally equivalent, fetid Berg Aukas Formation farther east (Hedberg 1979; Miller 2008) form a single-cycle, marker, cap carbonate succession that is up to 400 m thick in places. Algal mat roll-ups are a feature of the Rasthof Formation (Hoffman et al. 1998a, b; Hoffman and Halverson 2008). Pale grey dolomite grainstone that is locally brecciated and contains fragments enclosed in a fibrous isopachous cement, forms the top of the Rasthof Formation. The Gruis Formation in the western part of the Northern Platform consists of cycles of pink 'ribbonite' and grainstone averaging 1.5 m in thickness (Hoffman and Halverson 2008). Its equivalent farther east, the Gauss Formation**,** is commonly a massive, fragmented light grey dolomite in which fragments are rimmed by fibrous isopachous cement. This may have developed during rather passive slumping, but the solution and remobilization of evaporites in the formation could also be a cause of the fragmentation (Hedberg 1979). The Gruis and Gauss Formations have few stromatolites, suggesting rather deep water dep-

Table 2. Comparative lithostratigraphy of the Nosib Group and Ombombo Subgroup on the Northern Platform of the Damara Orogen in Namibia and the Roan Group in the Central African Copperbelt. Data are compiled from Hedberg (1979), Miller (1983a, 2008), Porada and Berhorst (2000), Cailteux et al. (2005a, 2007), Hoffman and Halverson (2008), Kampunzu et al. (2009) and in part from Selley et al. (2005).

NAMIBIA: Ombombo Subgroup (upper part), Nosib Group (lower part)	**Formation**	**Formation**	**ZAMBIA** & ***DRC*****:** Roan Group
Thin, upward-coarsening, deltaic cycles of brown-weathering siltstone, sandstone, conglomerate	Okakuyu	Mwashia *Mwashya* Subgroup	U Mwashia: shale, siliceous dolomite, conglomerate, oolitic chert, pseudomorphs after gypsum, upward shallowing & exposure. Local pyroclastics; hematite & pyrite in lower half L Mwashia: dolomitic shale, grey–black carbonaceous shale, sandstone; Lwava volcanics; Mufulira – 10-40 m thick shale-sandstone, shale-dolomite-sandstone cycles, oolites at top; hematite, pyrite, pyroclastics in places *DRC: massive, stratified and algal dolostones, dolomite grainstones; jasper beds, pyroclastics, hematitic*
D: 5-25 m thick cycles of conglomerate, sandstone, siltstone, topped by grainstone and pink dolomitic biostromes; N: minor	Devede (D) Upper Naauwpoort (N)	Bancroft *Kansuki, Mofya – R3.3* Kanwangungu *R3.2*	Cyclical dolomitic shale, sandy dolomite, dolomite, (ex: Carbonate Unit or U. Roan); start carbonate very abrupt; intrusive gabbros; *cyclical; argillaceous to dolomitic siltstone & dolomite, feldspathic sandstone, intrusive mafic rocks; volcaniclastics, numerous erosional surfaces and intraformational conglomerates in upper Kansuki*
		Kibalongo *RGS – R3.1*	Shale with grit (Antelope Clastics); *dolomitic siltstone*
B: purple slate, siltstone; pink limestone, grey dolomite, marly laminite, black limestone N: minor	Beesvlakte (B) Upper Naauwpoort (N)	Chingola *Kambove*	Cherty and argillaceous dolomite, dolomite, shale at top*; stromatolitic, talcose & carbonaceous dolomite, black carbonaceous dolomitic shale & siltstone*
		Pelito-arkosic *Upper dolomitic shales*	Sandstone, shale, dolomitic shale, dolomite at base; northern arenitic facies, southern finer grained facies with carbonates and evaporates; *dolomitic and carbonaceous shale, dolomite and sandy dolomite, sandstone, arkose*
		Copperbelt Orebody Member or Ore Shale *Kamoto*	Z & DRC: Shale, dolomitic shale and siltstone, sandstone; argillaceous, arenitic and stromatolitic dolomite, Na-rich evaporites replaced by microcline & oligoclase, iron formation; shale in south (basin) through shale-siltstone (slope) to bioherm+sabkha in north (littoral); 1st dolomite forms base of unit
N: >6600 m peralkaline ignimbrite, K-rich & Na-rich centers; very minor mafic ash-flows; A: Leucitite; associated Cu	Lower Naauwpoort /Askevold		
Pale pink feldspathic sandstone, scattered pebbles; conglomerate lenses; basal conglomerate	Nabis	Mutonda	Conglomerate, coarse arkose, argillaceous siltstone, minor eolian sandstone, rare dolomite; *often dolomite in DRC*
		Kafufya	High-Mg quartzites
		Chimfunsi	Red conglomerate

■ Rift arkoses

▦ Rift volcanics

▤ Waning rift volcanism & early platform clastics and carbonates

Table 3. Comparative lithostratigraphy of the Abenab Subgroup on the Northern Platform of the Damara Orogen in Namibia and the Nguba Group in the Central African Copperbelt. Data are compiled from Hedberg (1979), Miller (1983a, 2008), Porada and Berhorst (2000), Batumika et al. (2007), Hoffman and Halverson (2008), Kampunzu et al. (2009) and in part from Selley et al. (2005).

NAMIBIA: Abenab Subgroup	**Formation**	**Formation**	**ZAMBIA &** ***DRC*****:** *Nguba Group*
A: four cycles of brown shale & dolomite or limestone grainstone, oolitic layers towards top O: 8 x 25 m-thick limestone grainstone cycles	Auros (A) / Ombaatjie (O)	*Monwezi*	*Dolomitic sandstone, siltstone, shale*
		Katete	*N: dolomitic sandstone, siltstone, shale* *S: cyclical green to dark grey shale & laminated, purple to white, albite- & talc-bearing dolomite (pinches out to N)*
Ga: light-medium grey dolomite, often slumped; abundant fibrous, sparry, isopachous cement around fragments Gr: 1.5 m thick pink dolomite ribbonite - grainstone cycles	Gauss (Ga) / Gruis (Gr)	*Kipushi*	*Fine-bedded black dolomite, black chert, white oncolites; with cyclical, grey-brown dolomitic shale in S (thins to N)* (Auros equivalent?)
One 100 to 700 m-thick cycle; U: light grey dolostone grainstone M: laminated dolostone, algal roll-ups L: dark grey, laminated, dolostone cap, , 3-75 m thick;	Berg Aukas /Rasthof	Kakontwe (may be lateral equivalent of Kaponda – Porada and Berhorst 2000)	*Six-unit formation in north: basal light grey dolomite followed by five limestone units;* *Three-unit formation in south: namely,* *U: dark grey dolomite, black chert;* *M: brecciated light grey – purplish dolomicrite, sparite cement (Gauss equivalent?)* *L: Pyrite-rich, light grey dolomite, gypsum pseudomorphs, tortuous folds (Rasthof equivalent?)*
		Kaponda	*Calcareous to carbonaceous shale & siltstone; subgreywacke in NE that coarsens & becomes more proximal towards NE* *Base: Dolomie Tigrée – cap dolostone consisting of alternating dark & light grey laminae; up to 150 m thick*
Main diamictite, <<100 - 1000 m thick; BIF layers	Chuos	*Mwale (Grand Conglomérat)*	Diamictite, 200-1200 m thick, BIF lenses; some local pillow lavas

■ Snowball-Earth glacial units

▨ Cap carbonate succession

osition (Hedberg 1979). The uppermost formation in the Otavi Mountainland, the Auros Formation, consists, where fully developed, of four cycles of brown shale and dolomitic or calcareous grainstone, with oolitic layers towards the top of the formation. Maximum thickness is 450 m. The equivalent unit in the west, the Ombaatjie Formation, is made up of eight calcareous grainstone cycles averaging 25 m in thickness. Oolites and stromatolites occur towards the top of these two formations (Söhnge 1957; Hoffman and Halverson 2008; Miller 2008).

In contrast to the Chuos Formation, the glaciogenic, Marinoan-age Ghaub Formation at the base of the Tsumeb Subgroup (Table 4) is often only patchily developed. It is most extensive in the Northern Margin Zone and the Otavi Mountainland where it locally reaches a thickness of 2000 m (Grobler 1961 – equated with the Chuos Formation by him). Its clast suite is dominated by carbonate fragments derived from the underlying Otavi rocks. However, its cap carbonate succession, the Maieberg Formation, is laterally extensive and again a single-cycle marker unit of marl – limestone rhythmite up to 700 m thick in places (Hoffman and Halverson 2008; Hoffman 2011). A positively weathering, tan-coloured cap dolostone, the Keilberg Member (Hoffmann and Prave 1996), is a characteristic and widespread marker horizon at the base of the formation. Mass flows with intraformational clasts occur in places (King 1990). Dolomite tops the Maieberg Formation in the Otavi Mountainland. Numerous phyllite-dolomite cycles characterize the light grey Elandshoek Formation in the west but it is often massive in the Otavi Mountainland and in the Northern Margin Zone where occasional oolitic bands or stromatolites hint at its cyclical nature. Irregular bodies, bands and layers of white jasperoid are a characteristic feature. Kerogen specks occur in Elandshoek packstones in the Otavi Mountainland. The final unit of the Otavi Group is the Hüttenberg Formation, consisting of bedded grey to dark

Table 4. Comparative lithostratigraphy of the Tsumeb Subgroup and the Mulden Group on the Northern Platform of the Damara Orogen in Namibia and the Kundelungu Group and Biano Subgroup in the Central African Copperbelt. Data are compiled from Hedberg (1979), Miller (1983a, 1997, 2008), Porada and Berhorst (2000), Wendorff (2003, 2011), Batumika et al. (2007), Hoffman and Halverson (2008), Kampunzu et al. (2009) and in part from Selley et al. (2005).

NAMIBIA: Tsumeb Subgroup and Mulden Group	**Formation**	**Formation**	**ZAMBIA & *DRC*:** Kundelungu Group
U: cycles of vari-colored shale, sandstone, limestone, dolomite, casts after gypsum M: cycles of grey-black shale, siltstone and minor sandstone and limestone, minor casts after gypsum L: cycles of vari-colored shale, siltstone and minor sandstone	Owambo	*Biano SG*	*Arkose, conglomerate, argillaceous sandstone; unmetamorphosed; orogen-derived detrital muscovite (Tabular Kundulungu?)*
Cycles of grey to grey-green shale, grey siltstone & sandstone; black, carboniferous shale marker	Kombat	*Sampwe*	*Cycles of dolomitic shale and argillaceous to sandy siltstone*
U: light grey arkose, feldspathic sandstone & greywacke; fines upwards L: dark grey shale, minor feldspar-free siltstone & sandstone	Tschudi	*Kiubo*	*Cycles of purplish-red shale and dolomitic siltstone and sandstone; more arenaceous than Mongwe; some pink sandy limestone, pseudomorphs after anhydrite towards top of fm*
		Mongwe	*Cycles of purplish-red shales and dolomitic siltstones and sandstones*
Grey dolomite, chert layers; cycles of grainstone to packstone; cross-bedded silicified oolites; local black shale bands; massive dark grey fetid dolomicrite; stromatolites; 'augen' limestone (after anhydrite)	Hüttenberg	*Lubudi*	*Pink oolitic limestone & sandy carbonate beds*
4.2 m thick grey siliceous dolomite grainstone-laminite cycles; often massive in Otavi Mountainland; local kerogen in packstones; stomatolites	Elandshoek	*Kanianga*	*Cycles of greenish, pinkish to purplish grey, calcareous to dolomitic shale and siltstone, pink dolomitic microbialaminite toward top of fm*
Single cycle up to 400 m thick of laminated argillaceous limestone, plumb stromatolites, sea-floor aragonite fans; mass flow breccia lenses Basal 40 m - tan dolostone cap (Keilberg Member - marker)	Maieberg	*Lusele*	*Pink to grey micritic dolomite (Calcaire or Dolomie Rose – a few 10s of m thick); shale where dolomite absent*
Diamictite; often thin and only sporadically developed but can reach 2000 m in thickness; carbonate fragments usually abundant. A maximum of 1600 m of section separates the Chuos and Ghaub Formations on the Northern Platform but they are in contact with each other at the western end of the Northern Zone (Maloof 2000)	Ghaub	*Kyandamu (Petit Conglomérat)*	*Diamictite, often with abundant carbonate fragments; southward facies change from tillite to glaciomarine. Grand & Petit Conglomérates separated by 5000 m of sediment in centre of basin but in contact with each other in places along basin margins.*

■ Snowball-Earth glacial units ▨ Cap carbonate succession □ Molasse

grey dolomite with dark grey to black chert beds and local black limestone. Silicified and cross-bedded oolite beds and stromatolitic zones point to an upward shallowing during deposition. In the middle of the Hüttenberg Formation in the Otavi Mountainland are dolomites and several 1–4 m beds of limestone containing lenses of black, nodular chert, intracrystalline kerogen and nodules of black calcite pseudomorphs after anhydrite. One marker bed 1.4 m thick, the 'augen limestone' or 'augen dolomite' contains a high concentration of these nodules. Drill holes have intersected anhydrite at depth at this stratigraphic level (Miller 2008).

Continental Rupture

Final continental rupture in the Damara Orogen occurred during the Ghaub glaciation and only in the Southern Zone (Miller 2008; Miller et al. 2009a, b). The resulting basin was probably rather narrow and Red Sea-like, and was floored by oceanic crust that became the source of later syntectonic, Alpine-type serpentinites (Barnes 1982). The basin was swamped by pelitic greywackes of the Kuiseb Formation, much like the Gulf of California, and had a mid-ocean ridge that produced the mid-ocean-ridge basalts and gabbros and Besshi-type cupreous pyrite deposits of the Matchless Amphibolite Member (Goldberg 1976; Killick 1983, 2000; Miller 1983b; Breitkopf 1989). Rupture was accompanied by continental, passive-margin mafic volcanism on either side of the Southern Zone (Miller 1983b, 2008; de Kock 1989; Miller et al. 2009a, b) and by large-scale subsidence of the whole of the central Damara Belt. Initial carbonates (Karibib Formation) were followed by accumulation of up to 10 km of greywacke (Kuiseb Formation) throughout this region (Miller 1980, 1983a, 2008). The carbonates of the Karibib Formation are the lateral equivalent of the Tsumeb Subgroup carbonates. Carbon isotopes (Hoffman and Halverson 2008) strongly suggest that the top of the Karibib Formation is time equivalent (at least isotopically equivalent) to the top of the Tsumeb Subgroup. The Kuiseb Formation greywackes do not occur and have no equivalent on the Northern Platform.

Convergence, Subduction, Molasse, Flysch and Foreland Deposition, Continental Collision

Transpressive convergence of South America with the Congo Craton (Goscombe et al. 2003a, b; 2005a) and the Congo Craton with the Kalahari Craton (Miller 1983a, 2008) led to large-scale uplift, erosion and the deposition of syntectonic flysch, foreland and molasse successions. The Mulden Group forms a northern molasse on the Northern Platform. This was deposited during and subsequent to D_1, mainly from sources in the Kaoko Belt. It thickens northwards north of the Kamanjab Inlier (Fig. 2) and is proximal in the west and distal in the east (Hedberg 1979; Guj 1970; Miller 1997). It was folded together with the underlying Otavi succession during D_2 (Miller 1983a, 2008). The Mulden Group records a complete change from carbonate to siliciclastic sedimentation on the Northern Platform. Unconformable to paraconformable in marginal intramontane basins with local stratigraphic sequences (Frets 1969; Guj 1970), the Mulden Group forms a continuous, paraconformable cover on the rest of the Northern Platform (Söhnge 1957; Frets 1969; Guj 1970; Miller 1983a, 1997, 2008). Meteoric palaeokarst features associated with this paraconformity host the polymetallic Tsumeb and Kombat deposits (Söhnge 1964; Innes and Chaplin 1986; Lombaard et al. 1986). The Mulden Group is predominantly grey in the lower half and red or vari-coloured in the upper half, and consists of numerous upward fining cycles, many of which have a carbonate top in the upper parts of the group. Highly carbonaceous layers are also present. Rhombohedral voids after gypsum, some filled with calcite, occur in the upper half of the sequence (Hedberg 1979; Miller 1997, 2008).

In the Eastern Kaoko Zone, which forms the western part of the Northern Platform, tight short-wavelength folds in Otavi rocks overlie open folds in the Nosib Group, suggesting a décollement between the two groups, probably in the highly tectonized upper Beesvlakte Formation (Hoffman and Halverson 2008).

The deep Southern Zone with its floor of oceanic crust became the locus of collision between the Congo and Kalahari cratons. Northeast-directed subduction of this ocean floor beneath the leading edge of the Congo Craton, referred to as the Okahandja Lineament (Miller 1979; Downing and Coward 1981; Fig. 2), resulted in uplift and erosion of the frontal region of the Congo Craton and the Central Zone of the Damara Belt (Fig. 2). Greywackes thus generated (Hureb Formation) were deposited syntectonically in the closing Southern Zone Ocean (de Kock 1992; Miller 2008, 2009a, b). The foreland carbonate ramp and distal, largely feldspar-free flysch of the lower Nama Group (Germs 1972, 1974, 1995; Grotzinger and James 2000; Grotzinger et al. 1995; Saylor et al. 1995, 1998) was deposited on the depressed leading edge of the Kalahari Craton and was largely coeval and probably laterally continuous with the uppermost parts of the Hureb Formation (Grotzinger and Miller 2008). Following closure of the Southern Zone ocean and collision, the sediments derived from the Central Zone were deposited as a southern, feldspar-bearing molasse at the top of the Nama Group (Nomtsas Formation and Fish River Subgroup; Germs 1972, 1974, 1995; Miller 1983a, 2008; Miller et al. 2009a, b).

Lufilian Arc

The Katanga Supergroup succession and its structural features suggest events similar to those in the Damara Orogen (Porada and Berhorst 2000; Selley et al. 2005; Cailteux et al. 2007; Batumike et al. 2007; Kampunzu et al. 2009; Wendorff 2011; Master and Wendorff 2011). Northeast- to northwest-directed folding and thrusting (Coward and Daly 1984; Daly 1986) produced the four arcuate tectonostratigraphic zones of the Lufilian Arc, namely, the Katangan High, Synclinorial Belt, Domes Region and External Fold and Thrust Belt (Fig. 3). The Lufilian Arc is separated from the coeval, high-grade Zambezi Belt to the south by the northeast–southwest-trending Mwembeshi Shear Zone (Kampunzu and Cailteux 1999; Porada and Berhorst 2000; Key et al. 2001; Selley et al. 2005; Johnson et al. 2007; Kampunzu et al. 2009). To the north is the subhorizontal Foreland Basin (also called the Kundelungu aulacogen or palaeograben). Much of the Lufilian Arc stratigraphy may be cyclical in nature but there is insufficient detail in descriptions to be certain of this. In the following account, Zambian rock unit nomenclature is used, and DRC nomenclature is also provided in italics.

Intracontinental Rifting

At the base of the Lower Roan Group, fluviatile conglomerate, arkose, quartzite, siltstone, and minor evaporites and eolian sandstone of the Mindola Subgroup (Mindola Clastic Formation of Seeley et al. 2005; Table 2) are accepted as having formed in an intracontinental rift environment (Unrug 1988; Porada 1989; Binda 1994; Porada and Berhorst 2000; Selley et al. 2005). Wedge-shaped cross sections (Selley et al. 2005) are suggestive of half-graben depositional basins in a terrain with pronounced topographical relief (Mendelsohn 1961). The sediments vary rapidly in thickness and facies along strike (Porada and

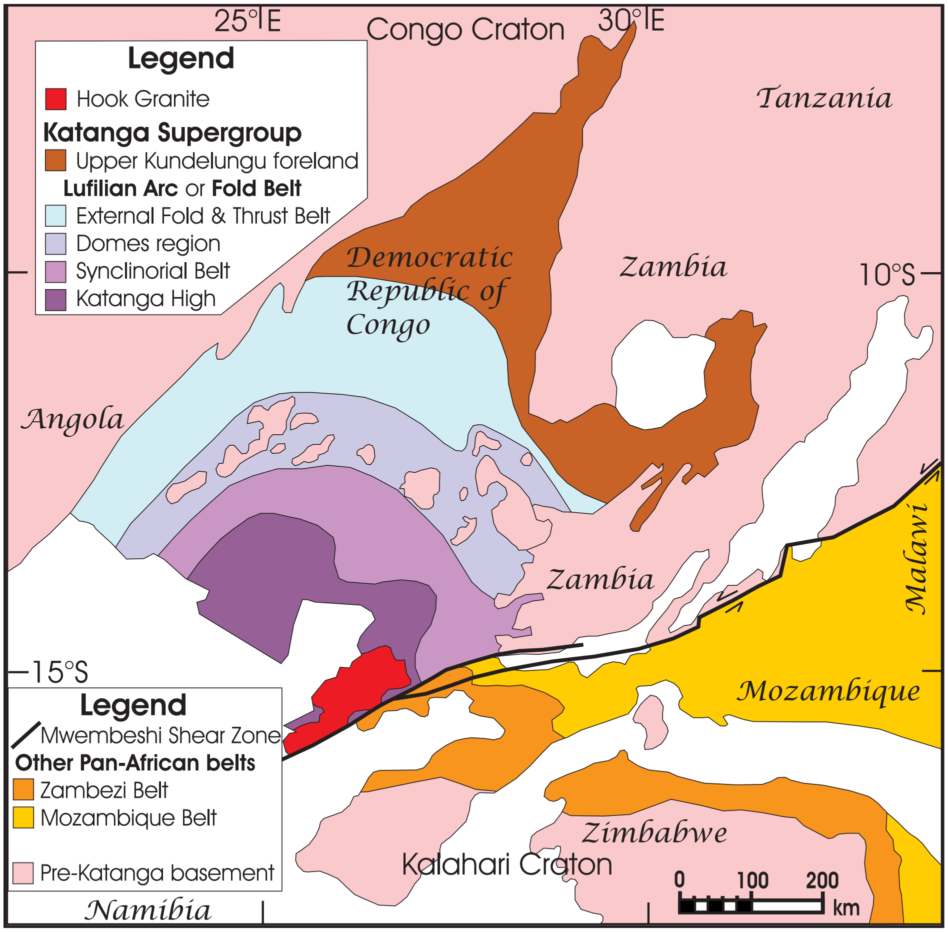

Figure 3. Structural zones of the Lufilian Arc or Fold Belt of the Central African Copperbelt relative to the upper Kundelungu Foreland Basin, the Mwembeshi Shear Zone and the coeval, high-grade Zambezi Belt (modified after Kampunzu and Cailteux 1999; Porada and Berhorst 2000; Key et al. 2001; Selley et al. 2005; Kampunzu et al. 2009).

Berhorst 2000; Selley et al. 2005), fine upwards, and are hematite-bearing (Cailteux et al. 1994). In the DRC, the equivalent *R.A.T. Subgroup* (Roches Argilo-Talqueuses) consists of an upward-fining succession of dolomitic and argillaceous sandstone and siltstone and dolomitic argillite (Cailteux 1994; Cailteux et al. 1994). Thickness is normally 200–300 m but reaches ~1 km locally (Selley et al. 2005). However, the Mindola Subgroup may thicken substantially to the north along a basinal axis in southern DRC.

Evolution from Rifting to Spreading

Thermal sag during slow extension, and occasional rejuvenation of the major rift faults accompanied by local mafic magmatism, facilitated basin-wide deposition. The first post-rift unit is the Kitwe Subgroup (Tables 1 and 2) or *Mines Subgroup*, which makes up the rest of the Lower Roan Group. At the base of this subgroup is the economically important Ore Shale Formation (Copperbelt Orebody Member; *Kamoto Formation* in the DRC; Table 2), which consists of shale; dolomitic shale and siltstone; arenite; siliceous, arenitic and stromatolitic dolomite; and pseudomorphs after evaporitic minerals (Selley et al. 2005; Kampunzu et al. 2009). It overlies the rift succession in some places and pre-rift basement in others (Selley et al. 2005) and appears to have been deposited during a significant flooding event. The overlying Pelito-arkosic Formation (*Upper dolomitic shales*) consists of proximal arenitic units in the north and finer-grained clastic rocks accompanied by carbonates and locally by evaporites in the south. Dolomites of the Chingola Formation (*Kambove Formation*) form the top of the subgroup, but an alternative interpretation is that they form a platform margin reef succession that separates a deeper basinal area with fine-grained siliciclastic rocks in the south from a restricted platformal facies in the north (Annels 1984; Binda 1994; Porada and Berhorst 2000).

The overlying Kirilabombwe Subgroup (*Dipeta Subgroup*) starts with a succession of shale and grit of the Kibalongo Formation (or Antelope Clastics), which is followed by widespread dolomite of the Bancroft Formation (Porada and Berhorst 2000; the upper Roan carbonates of Mendelsohn 1961). The dolomites include breccias with associated bodies of gabbro and amphibolite. Instead of being stratigraphically superposed one above the other, the carbonates may be a lateral, shallow-water facies of the Kitwe Formation (Annels 1974, quoted by Porada and Berhorst 2000; Annels 1984). The uppermost part of the dolomites in the DRC, the *Kansuki Formation*, contains silica-poor volcanic rocks that extend into Zambia (Cailteux et al. 2007) as the basaltic to andesitic Lwavu volcanics (Key et al. 2001). These DRC volcanic rocks have been interpreted as having been erupted in a continental rift environment (Kampunzu et al. 1993, 2000; Tembo et al. 1999; Cailteux et al. 2007). The overlying Mwashia Subgroup (*Mwashya Subgroup*) either overlies the Kirilabombwe Subgroup transgressively or structurally overlies it along a thrust (Porada and Berhorst 2000). The Mwashia consists dominantly of dolomitic to carbonaceous shales and local tectonic rafts of mafic rocks (Porada and Berhorst 2000; John et al. 2003). In the DRC, shallow-water carbonates are common, along with mafic and felsic pyroclastic rocks in the lower half of the unit; pseudomorphs after anhydrite and gypsum occur in the middle of the subgroup (Cailteux 1994; Cailteux et al. 2007).

The overlying, carbonate-dominated succession is divided into a lower Nguba Group and an upper Kundelungu Group by Batumike et al. (2007) but forms the Lower and Upper parts of the Kundelungu Group of Selley et al. (2005). Glacial units constitute the basal formation in each of these two groups (Tables 1, 3, 4). In the *Nguba Group* (Table 3), north to south facies changes accompany a southward thickening with a concomitant increase in the proportion of carbonate and a decrease in grain size of siliciclastic rocks (Batumike et al. 2007; Kampunzu et al. 2009; Table 3). The clast suite of the glaciogenic *Grand Conglomérat* or *Mwale Formation*, which reaches 1300 m in thickness (Batumike et al. 2007; Master and Wendorff 2011), is dominated by pre-Katangan rocks, but locally, clasts from the underlying Roan Group are abundant. Banded iron formation occurs in this unit (Porada and Berhorst 2000; Key et al. 2001; Wendorff and Key 2009). Kampunzu et al. (2009) consider that the overlying Kaponda, Kakotwe and Kipushi Formations form a cap carbonate succession. Nevertheless, it is the *Kaponda Formation* that has the greatest resemblance to a massive transgressive succession. This consists primarily of calcareous shale, siltstone and proximal subgreywacke (Batumike et al. 2007). In the DRC, 150 m of alternating dark and light grey laminae of the *Dolomie Tigée* form a typical cap dolostone at the base of the formation. This laminated unit contains algal mat roll-ups identical to those in Namibia (Batumike et al. 2007; Master and Wendorff 2011). The overlying *Kakontwe Formation*, so named in both the DRC and Zambia, is calcareous in the north-central parts of the DRC Copperbelt but dolomitic farther south (Batumike et al. 2007), where parts of it which consist of brecciated, light grey to purplish dolomicrite cemented by sparite are reminiscent of the Gauss Formation in the Otavi Mountainland. Nevertheless, this is retained as a cap carbonate succession and Maieberg equivalent in Table 3. The Kipushi, Katete and Monwezi Formations (Kundelungu Shale Formation of Selley et al. 2005) may be the equivalent of the Auros Formation. The *Kipushi Formation* consists of thinly bedded black dolomite with black chert and white oncolites in the north, and cyclical grey-brown dolomitic shale in the south. The *Katete* and *Monwezi Formations* consist of cyclical green to dark grey shale and laminated purple to white, albite- and talc-bearing dolomite in the south, passing into a proximal dolomitic sandstone, siltstone and shale facies in the north (Batumike et al. 2007).

The Nguba Group records large-scale differential subsidence within the Katangan basin, such that 5000 m of section separates the Grand and Petit Conglomérat in the southwestern regions. In contrast, these two diamictites form a contiguous, 250 m thick, glaciogenic succession in parts of the basin margin (Porada and Berhorst 2000). A similar scale of differential subsidence is recorded in the Damara Orogen, where 4000 m of section separate the Chuos and Ghaub Formations in the eastern part of the Northern Zone (Fig. 2), although they are in contact with each other in the west (Maloof 2000; Hoffman and Halverson 2008).

Stratigraphy Associated with and Following Possible Continental Rupture

Continental rupture is assumed to have taken place during deposition of the Petit Conglomérat, as it did during deposition of the Damaran Ghaub Formation, and presumably in the Zambezi Belt, as it did in the Southern Zone of the Damara Orogen.

Except for the Mufulira area, the Kundelungu Group (Table 4) is poorly represented in Zambia. In the DRC it is divided into *Gombela, Ngule* and *Biano Subgroups* (Batumike et al. 2007). The glaciogenic *Petit Conglomérat Formation* (also called the Petit Conglomerate Formation or *Kyandamu Formation*) at the base of the Gombela Subgroup, like the Ghaub Formation, is only intermittently developed. A southward facies change from tillite to glaciomarine sedimentation is accompanied by a decrease in thickness from a maximum of 100 m and a marked decrease in clast size from 1 m to < 2 cm. Clasts are from extrabasinal and intrabasinal sources (Master and Wendorff 2011). The *Lusele Formation*, consisting of pink to grey dolomicrite known as the Calcaire Rose or Dolomie Rose, is a few tens of meters thick and forms the cap carbonate. Where carbonate is absent, shale rests directly on the Petit Conglomérat (Master and Wendorff 2011). The *Lusele Formation* is overlain by up to 1000 m of cyclic, greenish, pinkish to purplish grey, calcareous to dolomitic shales and siltstones of the *Kanianga Formation* (Upper Kundelungu Shales of Selley et al. 2005). Layers of pink, dolomitic microbial laminite cap some of the cycles toward the top of the formation. Up to 150 m of pink, thickly bedded limestone of the *Lubudi Formation* forms the top of the Gombela Subgroup.

The *Mongwe* and *Kiubo Formations* of the overlying *Ngule Subgroup* together reach some 600 m in thickness (Batumike et al. 2007). Both consist of interbedded purplish-red shales and dolomitic sandstones and siltstones. The *Kiubo Formation* is the more arenaceous of the two and contains some layers of pink sandy limestone and, towards the top of the formation, pseudomorphs after anhydrite.

Convergence and Deformation, Foreland Basin Deposition

Coward and Daly (1984) and Daly (1986) recognize two phases of northeast- to northwest-directed folding and thrusting, some of which may have been facilitated by the evaporites in the Mwashia sequence (Kampunzu and Cailteux 1999; Cailteux et al. 2007).

Although Batumike et al. (2007) place the *Sampwe Formation* at the top of the Ngule Subgroup, they point out that it occurs at the northern edge and north of the folded and thrusted rocks of the Lufilian Arc, has a subhorizontal attitude, and forms the base of the Katangan succession in the northern plateaus. Batumike et al. (2007) suggest that the southernmost Sampwe rocks lie discordantly on folded Kiubo rocks. The *Sampwe Formation* is up to 1700 m thick and consists of alternating dolomitic shales and argillaceous to sandy siltstones. Conformably above this are some 400 m of subhorizontal, carbonate-free arkoses, argillaceous sandstones and conglomerates of the *Biano Subgroup*, which is derived from basement to the north as well as from the advancing thrust sheets of older Katangan rocks to the south (Wendorff 2003, 2011; Master et al. 2005). Together, the tabular Sampwe and Biano rocks form the Kundelungu and Biano Plateaus.

Wendorff (2000a, b; 2003, 2011), in a somewhat controversial reshuffling of the stratigraphy, places a major early D_1 unconformity at the top of the *Kiubo Formation*. He suggests that his Fungurume Group overlies this unconformity and consists of syn-D_1, deep-water, nappe-front olistostromes overlain by conglomeratic marginal marine and continental units, all of which were overridden during D_2 by older Katangan rocks and are now tectonically interleaved with such Katangan rocks. There is a marked northward decrease in size of fragments in the olistostromes. In this scenario, the Biano rocks form a molasse succession slightly younger than the foreland Fungurume Group (Kampunzu and Cailteux 1999; Wendorff 2003, 2011). The 'olistostromes' are the tectonic breccias of other workers (Cailteux et al. 1994, 2005a, b; 2007; Kampunzu and Cailteux 1999; Kampunzu et al. 2005; Batumike et al. 2007); some may be the result of salt tectonics (Jackson et al. 2003). The olistostromes/breccias contain megablocks up to 800 m across and fragments of mineralized Roan strata.

Alteration

Calcium-magnesium, potassic, sodic and limited silicic alteration, some of it multistage and some locally very intense, affected much of the Roan Group during diagenesis, ore formation and deformation (Selley et al. 2005 and references therein). Much of this alteration is concentrated in or near the Ore Shale Formation but extends well beyond mineralized zones and as far up the stratigraphy as the Mwashia Subgroup as well as into the underlying basement. Ca- and Mg-bearing phases in siliciclastic and carbonate rocks and in breccias are anhydrite, calcite, dolomite, phlogopite and Mg-chlorite. These are typical of sabkha environments and/or Mg metasomatism. K-feldspar, phlogopite and sericite typify the potassic alteration. Diagenetic K-feldspar mantles detrital K-feldspar, replaces detrital plagioclase and, under metasomatic conditions, can become the dominant mineral phase in precursors that were initially argillaceous and Al rich. Fine-grained sericite is the main potassic alteration phase where hydrocarbons or H_2S may have been present. Secondary albite and scapolite result from sodic alteration. Albite overgrows or replaces sericite and K-feldspar and Na concentration generally increases upwards in the section. Albite enclosing tourmaline laths is locally an abundant matrix phase in the breccias, and albitization commonly extends outwards from such breccias.

CHRONOLOGICAL COMPARISON

Pre-Katangan and Pre-Damaran Basement

In Zambia, the youngest pre-Katangan rock (Table 5) is the Neoproterozoic Nchanga Granite (883 ± 10 Ma; Armstrong et al. 2005). Pre-Nosib basement in Namibia is Paleoproterozoic to Mesoproterozoic in age (Miller 1983a, 2008). The oldest ring complex of the anorogenic Richtersveld Intrusive Suite adjoining the Gariep Belt in southwestern Namibia – the older Bremen Complex – has pre-rift(?) ages of 906 ± 22 Ma (U–Pb multiple zircon) and 903 ± 14 Ma (Rb/Sr) (Allsopp et al. 1979, recalculated by Frimmel 2008).

Rifting

Lower Roan Group and Nosib Group

In Zambia, basal conglomerates of the lower Roan Group contain 877 ± 11 Ma zircons derived from the unconformably underlying Nchanga Granite (Armstrong et al. 1999). Hanson et al. (1994) and Porada and Berhorst (2000) suggest that this granite, together with the Kafue rhyolites (879 ± 19 Ma; Hanson et al. 1994) and the associated Nazingwe metabasalts in the Zambezi Belt, relate to continental extension and rifting that started at about 880 Ma (Hanson et al. 1994). Johnson et al. (2007) report ages of 880 ± 12 Ma and 876 ± 10 Ma for the Kafue rhyolites, 880 ± 14 Ma for a Nazingwe rhyodacite, and 829 ± 9 Ma and 820 ± 15 Ma for the Lusaka Granite, which intrudes higher stratigraphic levels. Hanson et al. (1994) and Porada and Berhorst (2000) suggest that the alkaline basal Rushinga Igneous Complex (804 ± 10 Ma; Vinyu et al. 1997) in the southern Zambezi Belt, and alkaline and carbonatitic complexes in the Western Rift of the DRC (830 ± 51 to 803 ± 22 Ma; Kampunzu et al. 1998) date the end of rifting (Table 5).

The start of Damara deposition is undated and has only been estimated at about 900–800 Ma (Miller 1983a, 2008). Unmetamorphosed dolerites that intrude the Mesoproterozoic Sinclair Supergroup at Rehoboth south of Windhoek but are not in contact with any Damaran rocks fall on a Rb–Sr reference line with an age of 821 ± 33 Ma (Ziegler and Stoessel 1993). This may be a syn-rift age. Available Nosib ages record the approximate end of rifting, namely 752 ± 7 Ma for zircon from lower Naauwpoort Formation lavas (de Kock et al. 2000), whole rock Rb–Sr of 764 ± 60 Ma for Lofdal Nepheline Syenite (Hawkesworth et al. 1981, 1983), and 757 ± 2 Ma for zircon from the Oas Syenite (Hoffman et al. 1994). Both syenites are associated with Naauwpoort volcanism (Frets 1969). Frimmel (2008, 2009) and Frimmel and Miller (2009a) associate the younger intrusions of the Richtersveld Intrusive Suite, which yield single zircon U–Pb ages between 831 ± 2 and 771 ± 6 Ma, with crustal thinning during rifting.

The Zambezi Orogeny

Several orthogneisses in the Zambezi Belt have emplacement ages of between 880 and 780 Ma and a mean thereof of 830 ± 28 Ma (n = 36) (Goscombe et al. 2000). These ages have been interpreted as recording a compressive orogenic event, the Zambezi Orogeny, under upper amphibolite metamorphic conditions (Barton et al. 1991). This event is not recorded in the Namibian Pan-African belts nor the Lufilian Arc. Some structural and geochemical evidence, however, suggests emplacement of the orthogneisses during extensional rather than compressional tectonics (Goscombe et al. 2000) which is supported by the interpretations of Hanson et al. (1994), Porada and Berhorst (2000) and Johnson et al. (2007) presented above. Thus, it seems questionable whether there was a 'Zambezi Orogeny.'

Gradual Transition from Rifting to Spreading

There is little evidence for any spreading in the Northern Platform but the stratigraphy of the central Damara Orogen indicates a slow transition over almost 120 my, i.e. from about 752 Ma to 635 Ma, from rifting to continental break up (Miller 2008; Miller et al. 2009a, b). The first deposition of carbonates and fine siliciclastic rocks above rift-related arkoses record the

Table 5. Comparative stratigraphic, structural, metamorphic and plutonic evolution of the Damaran and Katangan Supergroups. See text for references to ages.

Damaran, Northern Platform *(and Kaoko and central Damara Belts)*	Ma	Ma	Katangan *(and Zambezi Belt)*
Karsting, oxidation, vanadates; from Cretaceous into Tertiary	Cretaceous - Tertiary	Cretaceous - Tertiary	Karsting, oxidation, vanadates; from Cretaceous into Tertiary
Cooling	490 - 460	510 - 467	Cooling
U-bearing alaskite in Central Zone	510	512	Mineralization; metamorphism?
Tsumeb pipe	531		
Peak post-D$_3$ - M$_2$ metamorphism	535	533 538	Post-tectonic Hook Granite Post-tectonic rhyolite dyke
Continental collision in Southern Zone = D$_3$	542	529 -532	*Whiteschist metamorphism & continental collision; D$_3$? (monazite in whiteschist shear zone)*
D$_3$; open folds	542		D$_3$; open folds; age?
D$_2$; *thrusts, decompression*	~550		D$_2$, thrusts, decompression, *low-P amphibolite facies metamorphism,* weak S$_2$
Pre-D$_2$ granites (Central Zone)	565 -555	551 566, 559	Rhyolite in Mwembeshi Shear Zone Syntectonic Hook Granite
Mulden molasse	595 -550	600 -550 ?	U Kundlungu & Biano Group (detrital muscovite – 638, 573 Ma)
D$_1$, M$_1$; *isoclinal sheath folds, thrusting; strong S$_1$ axial planar foliation; staurolite-kyanite (Damara Central Zone & Kaoko Belt)*; karsting of Tsumeb Subgroup	595	659 ?; 595 -592	D$_1$, M$_1$; isoclinal folding, thrusting; strong axial planar S$_1$ foliation; eclogite facies metamorphism at ~607 Ma
Tsumeb Subgroup	635 - ±600		L Kundulungu, Gombela Subgroup
Hartelust Rhyolite Member	609		
Ghaub diamictite; continental rupture, sea-floor *MORB in Southern Zone*	635	?635?	Petit Conglomérat (Kyandamu Fm)
Abenab Subgroup			Nguba Group
Chuos diamictite	<746	~735	Grand Conglomérat: Mwale Fm
Ombombo Subgroup; final Naauwpoort volcanism	746	745 -765	U Roan; Mwashia SG: gabbro – 745, 753 Ma; Lwavu volcs – 763, 765 Ma
End-Nosib volcanism	756	?	End L Roan,
		820	Intrusion of Lusaka Granite
Nosib			L Roan
Start rifting/Nosib deposition		~877, 879	Start L Roan deposition (RAT 1 & Mindola Subgroup); *Kafue Rhyolite (879 Ma);* Nchanga A-type Granite (877 Ma)
Youngest pre-Damaran age	903	883	Youngest pre-Katangan age

beginnings of this long, slow evolution. Pulses in rejuvenation of rift faults and spreading are marked by local mafic volcanic or intrusive rocks along the margins of the Southern Zone of the orogen (i.e. the Vaalgras Subgroup in the Southern Margin Zone, and the Daheim, Omusema and Lievental Members of the Ghaub Formation in the southern Central Zone and just north of the Okahandja Lineament; Miller 2008).

Upper Roan Group and Ombombo Subgroup

Extensional evolution from rifting to a 'proto-oceanic rift stage' (Kampunzu et al. 2009) took place in the Katanga Basin from about 765 to 735 Ma (Porada and Berhorst 2000; Key et al. 2001). Lwavu basalts and basaltic andesites in the Mwashia Subgroup yielded U–Pb zircon ages of 765 ± 5 Ma and 763 ± 6 Ma (Key et al. 2001). In the Ombombo Subgroup, ignimbrites of the volumetrically minor upper Naauwpoort Formation within the Devede Formation gave an age of 759 ± 1 Ma (Halverson et al. 2005). A feeder dyke to an upper Naauwpoort rhyolite that directly underlies the Chuos Formation (Miller 1980) has been dated at 746 ± 2 Ma (Hoffman et al. 1996).

Nguba and Abenab Subgroups

Brecciated and altered porphyries in a breccia containing iron formation fragments and apparently closely associated with diamictite yielded a U–Pb zircon age of 735 ± 5 Ma (Key et al. 2001). Key et al. (2001) state that these volcanic rocks overlie the Grand Conglomérat but Kampunzu et al. (2009) regard them as being part of the Grand Congomérat.

Continental Rupture

Kundelungu and Tsumeb Subgroups

The only date available for these subgroups is that of an ash in the glaciogenic Ghaub Formation just below the tan cap carbonate (Keilberg Member) in the central Damara Orogen; this ash yielded a zircon age of 635.5 ± 1.2 Ma (Hoffmann et al. 2004). Miller (2008) and Miller et al. (2009a, b) consider this to be the approximate age of continental rupture in the Southern Zone of the Damara Belt. The MORB-type chemistry of eclogites in the Zambezi Belt is the only indication of possible ocean floor there (John et al. 2003). A layer of fragmented rhyolite, the Hartelust Rhyolite Member (Miller 2008), occurs along the southern margin of the Damara Belt at a level approximately equivalent to the top of the Karibib and Hüttenberg Formations. Zircons from the rhyolite have yielded a lower intercept U–Pb age of 609 +3/-15 Ma (Nagel 1999). This would mean that the 10 km of greywacke in the overlying Kuiseb Formation were deposited in the ca. 15 my period between this date and those for the first syntectonic metamorphic minerals.

Convergence

In the Lufilian Arc, the oldest metamorphic ages are 592 ± 22 Ma (U–Pb monazite) and 585.8 ± 0.8 Ma (^{40}Ar–^{39}Ar plateau age for biotite; Rainaud et al. 2002). Early deformation during subduction in the Zambezi Belt is recorded by the Sm–Nd garnet – whole rock age of eclogite formation of 595 ± 10 Ma (John et al. 2003). Hanson et al. (1993) record a spectrum of syntectonic to post-tectonic U–Pb zircon ages from the Hook Granite (Fig. 3) and associated rhyolite dykes at the southeastern edge of the Lufilian Arc: syntectonic granite (566 ± 5 Ma and 559 ± 19 Ma); a syntectonic rhyolite dyke in the Mwembeshi Shear Zone (551 ± 19 Ma); undeformed, post-tectonic rhyolite within the granite massif (538 ± 1.5 Ma); and a post-tectonic phase of the granite (533 ± 3 Ma).

Almost identical to early Lufilian metamorphic ages is the Sm–Nd age of 595 ± 13 Ma for syn-D$_1$, peak-M$_1$ garnet in the Coastal Terrane of the Kaoko Belt (Goscombe et al. 2003a). Goscombe et al. (2003a, 2005b) also record other peak-M$_1$ garnet ages of 579 ± 16, 574 ± 10 and 573 ± 8 Ma, and a U–Pb age of 573.8 ± 4 Ma for zircon from a partial melt segregation in other Kaoko Belt zones. In the same belt, zircons from the earliest Damaran granites give U–Pb ages of 580 ± 3 Ma (Seth et al. 1998), 576 ± 5 Ma (Franz et al. 1999) and 576 ± 11 (Goscombe et al. 2005b). A slightly younger granite in the Kaoko Belt has an age of 568 ± 5 Ma (Goscombe et al. 2005b) and ages of granites reported as being late tectonic range from 565 ± 13 Ma (Seth et al. 1998) to 549.2 ± 1.9 Ma (Goscombe et al. 2005b). In the central Damara Belt, post-D$_1$ – pre-D$_2$ to early-D$_2$ granites have ages ranging from 564 ± 5 to 546 ± 30 Ma (Haack et al. 1980; Miller and Burger 1983; Hawkesworth et al. 1983; de Kock et al. 2000; Jacob et al. 2000).

Ages of detrital white micas in the syntectonic successions record the unroofing and erosion of adjoining high-grade zones. Those in the Biano Group molasse (Katanga Belt, Kundelungu Group) yield ^{40}Ar–^{39}Ar plateau ages of 638 ± 4 and 573 ± 5 Ma (Master et al. 2005). Almost identical are those of 643 Ma (mean of 15 ages) and 576 Ma (mean of 15 ages) throughout the foreland succession of the Nama Group in the Damara Belt (Zimmermann 1984; Horstmann et al. 1990; Grotzinger and Miller 2008). The older age is identical to that of the 640 Ma terrane in the Dom Feliciano Belt of eastern South America (Basei et al. 2000), from which such micas (at least in the Nama Group) must have been sourced during convergence in the Kaoko and Gariep Belts. The younger ages probably correspond to early metamorphism and unroofing in the Zambezi and central Damara Belts, respectively.

Thin volcanic ash beds in the Nama Group date the final stages of convergence just prior to continental collision in the Damara Belt. The stratigraphically lowest of these is approximately halfway up the foreland succession and yielded a ^{207}Pb–^{206}Pb age of 548.8 ± 1 Ma; the highest ash bed in the foreland succession is just a few meters below the Precambrian – Cambrian unconformity at the base of the Nomtsas Formation and has an age of 543.3 ± 1 Ma (Grotzinger et al. 1995).

The direction of convergence in the Kaoko Belt gradually rotated from initially sinistral transpressive to orthogonal during final continental collision (Goscombe et al. 2003a). The same style of rotation applied in the Damara Belt (Miller 2008; Miller et al. 2009a). It was during the late stage of orthogonal compression that deep stratigraphic levels along the northern edge of the Northern Zone were thrust approximately northwards along the Khorixas – Gaseneirob Thrust onto the Mulden molasse of the Northern Margin Zone (see Miller and Schalk 1980; Fig. 2). A similar structural evolution appears to have taken place in the Lufilian Arc. The Mwembeshi Shear Zone is a transpressive feature with a sinistral sense of shear (Hanson et al. 1993; Batumike et al. 2007; Kampunzu et al. 2009), but the thrusts and arcuate zones in the Lufilian Arc have late-stage(?) northwest to northeast transport directions (Coward and Daly 1984; Daly 1986), almost orthogonal to the Mwembeshi Shear Zone and the coeval Zambezi Belt.

Collision

John et al. (2004) consider that the 530 ± 1 Ma U–Pb age of monazite in talc – kyanite schists dates final continental collision and the peak of final, low-temperature – high-pressure regional metamorphism that accompanied D_2 thrusting in the Lufilian Arc (Kampunzu and Cailteux 1999; Key et al. 2001). Continental collision took place in the Damara Belt during D_3 deformation (Miller 1983a, 2008; Miller et al. 2009a, b). Zircon from a syn-D_3 granite yielded a U–Pb age of 542 ± 6 Ma (Tack et al. 2002).

Post-Collision Events

Oldest Post-Collision Magmatism in the Damara and Kaoko Belts

In the Nama Group, zircon from an ash bed at the base of the Nomtsas Formation (southern molasse) and just above the Precambrian – Cambrian unconformity yielded a U–Pb age of 539.4 ± 1 Ma (Grotzinger et al. 1995). This is a post-collision date and matches that of the 539 ± 6 Ma (U–Pb zircon) age of the undeformed, post-tectonic Rotekuppe Granite in the central Damara Belt (Jacob et al. 2000). The oldest post-tectonic granites in the Kaoko Belt have ages of 541 +19/-17 Ma (U–Pb zircon – titanite; Retief 1988; Miller 2008), 540 ± 3 Ma (U–Pb zircon; van de Flierdt et al. 2003), and 530 ± 3 Ma (Pb–Pb zircon evaporation; Seth et al. 1998).

Peak M_2 Metamorphism

Zircon and monazite from a post-D_3, anatectic red granite generated during high-temperature, lower granulite facies metamorphism at Goanikontes in the western part of the central Damara Belt yielded a U–Pb age of 534 ± 7 Ma (Briqueu et al. 1980). This age is identical to those of <2μ white micas (537 ± 7 and 538 ± 12 Ma) generated during very low grade metamorphism of Mulden phyllites (Clauer and Kröner 1979), and the mean of 531 Ma throughout the foreland and molasse successions of the Nama Group, including the Fish River Subgroup (Ahrendt et al. 1977; Horstmann et al. 1990; Grotzinger and Miller 2008). This metamorphic age of the Fish River Subgroup molasse supports the observation that its trace fossils are of pre-trilobite Cambrian age (Geyer 2005). Falling within this group of ages is the Pb–Pb age of 530 ± 11 Ma for the largely post-tectonic mineralization of the Tsumeb polymetallic pipe (Kamona et al. 1999). Giving confidence to the 535 Ma age of Damaran M_2 metamorphism is the Rb–Sr whole-rock age of 527 ±3 Ma for the Donkerhuk Granite (Haack and Gohn 1988), which is post M_2 (Sawyer 1981).

Peak M_2 metamorphism in the Zambezi Belt is dated at between 543 and 532 Ma by U–Pb zircon and 530 to 525 Ma by U–Pb titanite and Ar–Ar hornblende (Goscombe et al. 2000).

Younger Post-Collision Events

Molybdenite from the auriferous veins in the Navachab gold skarn deposit near Karibib yielded a post-M_2 Re–Os age of 525 ± 2.4 Ma (Wulff et al. 2010). In the Kaoko Belt, U–Pb zircon and monazite ages of post-collision granites or pegmatites range from 531 ± 6 to 507 ± 5 Ma (Goscombe et al. 2005b). In the southern Central Zone of the Damara Belt, similar late intrusions range from 509 ± 1 Ma (U–Pb uraninite in alaskite; Briqueu et al. 1980) to 496 ± 6 Ma (U–Pb titanite in lamprophyre; Jacob et al. 2000). Whole-rock Rb–Sr and zircon U–Pb both give an age of 495 Ma for the Sorris–Sorris Granite in the Northern Zone (Hawkesworth et al. 1983; P.F. Hoffman, quoted in Miller 2008). In the Lufilian Arc, veins with associated albitization have ages of about 514 and 510 Ma (Richards et al. 1988; Torrealday et al. 2000).

Cooling

Ar–Ar and Rb–Sr ages of muscovite and biotite from the Lufilian Arc and the Zambezi Belt record cooling ages of 510 to 465 Ma (Cosi et al. 1992; Goscombe et al. 2000; Torrealday et al. 2000; Rainaud et al. 2002; John et al. 2004). Cooling through 500°C is recorded in the Kaoko Belt by Ar–Ar plateau ages of 533 ± 7 to 513 ± 8 Ma for hornblende (Goscombe et al. 2005b), and in the Damara Belt by Rb–Sr (whole rock-muscovite) ages of 509 and 506 ± 7 Ma (Blaxland et al. 1979; Kukla 1993) and Rb–Sr (muscovite) of 520 and 524 Ma (Hawkesworth et al. 1983). In the kyanite facies of the high-pressure Southern Zone, Rb–Sr (muscovite) recorded a younger age of 483 Ma for cooling through 500°C (Hawkesworth et al. 1983). Damaran biotite cooling ages fall between 503 and 442 Ma (Clifford 1967; Haack and Hoffer 1976; Clauer and Kröner 1979; Ahrendt et al. 1983; Hawkesworth et al. 1983; Weber et al. 1983).

Cretaceous – Tertiary Modification

Most of the carbonate-hosted base metal deposits in the Otavi and Katangan successions were strongly oxidized during the Cretaceous African Erosion Cycle and during the Tertiary, at which time they developed vanadium-bearing supergene caps and supergene facies in deep-penetrating shear zones (Innes and Chaplin 1986; Lombaard et al. 1986; Kamona et al. 1999; Kamona and Friedrich 2007). The end-Cretaceous, African Erosion Cycle regolith is preserved beneath and protected by a continuous sheet of massive, unevenly layered groundwater calcrete from north of Kamanjab to the Opuwo area (Fig. 4). This calcrete is distinct from the nodular textures of pedogenic calcretes. Within the regolith, pre-Damaran rhyolites and Nosib arkoses are white and totally sericitized (Fig. 4). Average thickness of the regolith is 30–50 m, but Jennings and Bell (2011) record extensive oxidation of copper occurrences in this area to depths of up to 200 m. It is conceivable that sulphuric acid generated from oxidation of sulphides during the African Erosion Cycle facilitated far deeper penetration of late Cretaceous – early Tertiary alteration.

Figure 4. Main photograph – the background shows the bevel of the African Erosion Surface south of Opuwo. Insets – A: The protective capping of end Cretaceous – early Tertiary, indistinctly layered but massive groundwater calcrete on the African Erosion Surface in the main photograph; B: white, completely kaolinized Nosib Group arkose in the African Erosion Surface regolith beneath the calcrete capping in 'A'; C: the normal, pale pinkish brown colour of unaltered Nosib Group arkose from the Dordabis area southeast of Windhoek.

COPPER MINERALIZATION IN THE EASTERN KAOKO ZONE

The most comprehensive published descriptions of copper mineralization are provided by Jennings and Bell (2011) and Maiden and Freyer (2012). These authors record some 200 copper occurrences in the Eastern Kaoko Zone, far more than initially recorded by Schneider and Seeger (1992). There are a few occurrences of disseminated mineralization or mineralization in quartz–calcite veins in arenites or conglomerates at the top or base of the Nosib or in shear zones in basement gneiss just below the Nosib; however, by far the majority of occurrences are stratabound and hosted by siltstones, schists or dolomites near the base of the Beesvlakte Formation, i.e. the Omivera and lower Omao formations of Jennings and Bell (2011).

Much of the mineralization exposed on surface is in quartz – calcite ± chlorite ± mica veins. However, more typical Copperbelt-style disseminated mineralization occurs in siltstone and schist in the Omivera and immediately overlying lower Omao formations in several localities, the largest or more typical of which are on the farms Tzamin 228 and Vaalwater 283 on the edge of Kamanjab Inlier and near the village of Okohongo (Fig. 2). These deposits lie just above the contact of the Beesvlakte Formation with the Nosib arkoses and conglomerates. Some occurrences consist of stratabound stockworks of mineralized, bedding-parallel and cross-cutting quartz – calcite ± chlorite ± mica veins confined to the same Omivera and Omao horizons. Other stockworks occur in adjacent dolomites, which may also be brecciated, or in dolomite of the upper Omao formation. In the Horseshoe deposit, some of the veins in the host schist parallel the foliation, suggesting a syn- to post-tectonic origin. This, in turn, suggests a possible two-stage mineralization process, the first forming the disseminated, stratabound deposits and the second the vein stockworks. Sulphides that core supergene minerals are chalcopyrite, bornite and chalcocite; pyrite may also be present. Supergene minerals are mainly malachite and chrysocolla, with or without chalcocite, dioptase and some rarer minerals, and local small quantities of galena.

DISCUSSION

Although there are key similarities between the almost coeval evolution of the Damara Supergroup on the Northern Platform of the Damara Orogen and the Katanga Supergroup in Central Africa, there are significant differences between the two successions. The Roan Group contains far more evaporitic minerals than the equivalent Ombombo Subgroup (Table 2). Lufilian salt tectonics (Jackson et al. 2003) has no matching record in Namibia. Lufilian thrust tectonics contrasts markedly with the folded margins of the Damaran Northern Platform, although there is some thrusting in the western part of the Eastern Kaoko Zone (Miller and Schalk 1980; Hoffman and Halverson 2008) along with some evidence of large-scale syn-sedimentary slumping (Hoffman and Hartz 1999). Neither the Lufilian breccias, whether olistostromes or of tectonic origin, nor the intense (Ca, Mg, Na, K) alteration have equivalents in the Otavi Group. Mineralization in the Lufilian Arc is far more extensive than in the Otavi Group and most mineral deposits occur in or within 200 m of the Ore Shale Formation (Selley et al. 2005). However, the mineral potential of the Beesvlakte Formation in Namibia, the equivalent of the Ore Shale Formation, needs further consideration, particularly in the light of the known, largely discordant mineralization in it and of the supergene nature of much of the mineralization (Schneider and Seeger 1992; Jennings and Bell 2011). Comparative consideration also needs to be given to the syn-deformational origin of the Lufilian mineralization and to the proposal that early extensional faults in the basal Roan arkoses were the primary conduits up which basinal fluids were delivered to receptive host rocks (Selley et al. 2005). Significant thickness changes in the Nosib Group arkoses may suggest the presence of such rift-phase faults (Jennings and Bell 2011).

In both regions, the ore shales are underlain by red beds, a potential source for the copper mineralization (Hitzman et al. 2005). The pink, hematitic Nosib Group arkoses (Hedberg 1979) are thicker than the Mindola Subgroup clastic rocks, although the latter may thicken substantially to the north towards the depositional axis of the Katangan Basin. Contrasting structural styles above and below the argillaceous Beesvlakte Formation suggest that it is the locus of a significant décollement (Hoffman and Halverson 2008), which could have facilitated fluid flow and ingress. Selley et al. (2005) demonstrate that many of the mineral deposits in the Central African Copperbelt are closely related to faults in the Mindola Subgroup and to basement beneath the Ore Shale Formation, which strongly suggests that these faults were fluid-flow loci. Identifying similar faults in the Nosib Group in outcrop and below the cover of the Ombombo Subgroup may help to focus exploration activities and provide a better understanding of known copper occurrences, particularly where the Beesvlakte Formation is dark grey in colour and therefore potentially reducing. Such faults may be associated with conglomerate lenses in the Nosib Group or be reflected in sudden changes in facies or thickness of beds in the Ombombo Subgroup. The 'lagoonal' nature of the Northern Platform and its separation from the main orogen to the south by an east – west antiformal ridge in the region of the Kamanjab Inlier (Hoffman and Halverson 2008; Hoffman 2011), as well as the many exposure surfaces identified by Hoffman and Halverson (2008) as terminating depositional cycles, suggest that evaporites in the Otavi Group may have been somewhat more common than has hitherto been realized.

ACKNOWLEDGEMENTS

Comments by Cameron Allen and an anonymous referee leading to improvement of the manuscript are greatly appreciated. Eckhardt Freyer provided me with the published 2011 report of INV Metals Inc. and the excursion guide to the field excursion that followed the Copper Conference held by the Geological Society of Namibia in 2012.

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Received October 2012
Accepted as revised February 2013