Sedimentology and chemostratigraphy of the late Neoproterozoic carbonate ramp sequences of the Hüttenberg Formation (northwestern Namibia) and the C5 Formation (western central Democratic Republic of Congo): Record of the late post-Marinoan marine transgression on the margin of the Congo Craton

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Sedimentology and chemostratigraphy of the late Neoproterozoic carbonate ramp sequences of the Hüttenberg Formation (northwestern Namibia) and the C5 Formation (western central Democratic Republic of Congo): Record of the late post-Marinoan marine transgression on the margin of the Congo Craton

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Abstract

The Neoproterozoic Marinoan climatic event corresponded to the Snowball Earth-type glaciation, and is commonly marked by the deposition of diamictites and by a negative carbon isotope anomaly. This event was followed by a sudden return to a greenhouse climate and a rapid post-glacial transgression with deposition of cap carbonates. Although the cap carbonates and marine carbonate sediments at the base of the post-glacial period are well known in the literature, few studies focused on the end of the marine transgression, which is a prelude to the Pan-African Orogeny in Central Africa. In this paper, we present new descriptions of these carbonate rocks and a sedimentological study from key cores and outcrops in the Otavi Mountainland (Namibia) and West Congo belt (DRC) of the Hüttenberg Formation and the C5 Formation, respectively. Both successions show five main facies: (i) microbial ‘mounds’ and pinnacles, (ii) ooid-shoal barrier, (iii) evaporitic brackish lagoon, (iv) beach and (v) coastal sabkha. The Hüttenberg Formation consists of an open-marine mid-inner carbonate ramp setting including microbial mounds and pinnacles, and oolitic shoal-barrier islands. The C5 Formation exhibits a hypersaline inner carbonate ramp including an ooid- shoal barrier, an evaporitic brackish lagoon, a beach and a coastal sabkha plain. Sedimentological, chemostratigraphical and biostratigraphical comparisons between the C5 and Hüttenberg formations suggest these are coeval carbonate shelf deposits on the margins.
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50 of the Congo Craton, with a depositional age between 580 Ma and 540 Ma for both
51 formations.

53 **Introduction**

55 The Ediacaran Hüttenberg Formation, the youngest stratigraphic unit in the Otavi Group of
56 the Damara Supergroup in northwest Namibia, comprises a 900 m-thick succession of shales,
57 dolomitic limestones, oolitic limestones, and cherty dolostones. These were deposited in
58 shallow marine environments on the southern and northern passive margins of the Congo-São
59 Francisco (hereafter, C-SF) and Kalahari cratons respectively (Kamona and Günzel, 2007;
60 Figure 1). The sedimentary succession of the C5 Formation of the Cataractes Group (former
61 West Congolian Group), similar to that developed in the Otavi Platform, is also present along
62 the western flank of the Congo Craton in the Democratic Republic of Congo (DRC)
63 (Delpomdor et al., 2018). Both successions record the end of the marine transgression,
64 following Snowball Earth-type Marinoan glaciation (Kirschvink, 1992; Hoffman, 1999;
65 Hoffman et al., 1998; Kennedy et al., 2001; Hoffman and Schrag, 2002). They predate the
66 shutdown of the carbonate factory before the deposition of molasse sequences of the Mulden
67 Group in Namibia and the Mpioka Subgroup in DRC. No datable intrusive or volcanic rocks
68 and biostratigraphic fossils have so far been directly reported from these stratigraphic units
69 and the age of sedimentation of the sedimentary succession in this part of the Ediacaran
70 sedimentary cover of the C-SF and Kalahari cratons remains largely unconstrained.
71 Nevertheless, the Hüttenberg and C5 formations were constrained by carbon isotopes, which
72 reveal an upwards-increasing trend suggesting a depositional age between 635 and 580 Ma
73 (Halverson et al., 2005; Frimmel et al., 2006). Recent chemostratigraphic and biostratigraphic
74 re-interpretation of the C5 Formation attributed a maximum depositional age of 540 Ma
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(Delpomdor et al., 2018). However, a previous study focusing on the temporal carbon isotope trend of Hüttenberg Formation carbonates has considered this to be a Sturtian to Marinoan interglacial interval (Kaufman et al., 2010).

The principal objective of this paper is to contribute to the debate on the age of the Hüttenberg Formation. We present the results of a detailed study on two key sections in the Hüttenberg Formation and the C5 Formation which record the ultimate postglacial marine transgression, before the terminal Neoproterozoic Pan-African orogeny. Here, we describe the depositional characteristics of these two carbonate ramps with a focus on the litho- and microfacies, geometry, and stratigraphic architecture. Based on the new inferred depositional environments of the stratigraphic-equivalent C5 Formation in the DRC, an age for the Hüttenberg and C5 formations can be estimated.

Geological setting and stratigraphy

Regional geological setting

Widespread shearing and tectonic escape, post-tectonic magmatism, extension, rifting, and intracontinental mobile belt formation were common on the margin of the C-SF cratons in the period ~1000-720 Ma (Stanistreet et al., 1991; Tack et al., 2001; Kamona and Günzel, 2007). These tectonic events postdated the assembly of Rodinia and predated the breakup of this supercontinent. Rifting of the Rodinia supercontinent occurred successively as a series of eastward younging rift basins formed between 1100 and 950 Ma (Unrug, 1995) (Figure 1A). Separation of the C-SF cratons from Rodinia supercontinent started with the opening of Araçuaí Basin between the C-SF cratons at ca. 1000 Ma (Pedrosa-Soares et al., 2001), and between 999 ± 7 Ma and 912 ± 7 Ma along the western margin of the Congo Craton with the deposition of volcano-sedimentary units and intrusion of peralkaline granitoids of the Matadi
and Tshela/Seke Banza groups (Tack et al., 2001; Baudet et al., 2014) (Figure 1B). Rifting and opening of the Adamastor Ocean, between the Kalahari, C-SF and Rio de la Plata cratons, was initiated between 900-760 Ma and was marked by voluminous volcanic effusions and intrusions (Hoffman et al., 1996; McGhee et al., 2012; Miller, 2013). Rifting occurred as transtensional and transpressive events between the Kalahari and C-SF cratons, extended into the Zambezi rift basin, which opened the Khomas-Mozambique Oceans with the deposition of fluvial clastics, intrusion of granitoids and outpouring of lava flows at 880 Ma (Martin, 1965; Hedberg, 1979; Porada and Berhorst, 2000; Armstrong et al., 2005; Li et al., 2008). Rifting spread westwards into the Zambezi and Damara rift basins, and thereafter northwestwards into the area of the Katanga rift Basin (Porada and Berhorst, 2000).

Between 920 Ma and ~600 Ma, a series of passive margins with deposition of fluvio- to marine siliciclastic and carbonate sediments developed along the margins of the C-SF cratons. The Amazonian–West African–Rio de la Plata cratons (East Gondwana) collided with West Gondwana, creating the Pan-African–Brasiliano orogenic belts on the margin of the C-SF cratons between ~650 Ma and ~515 Ma (Alkmim et al., 2006; Pedrosa-Soares and Alkmin, 2011) (Figures 1D, E). West Gondwana was amalgamated with Amazonia, West Africa and C-SF plates at about ~600 Ma (Brito-Neves et al., 1999; Cordani et al., 2003) initiating the earlier Pan-African–Brasiliano tectonic episode of the Araçuaí-West Congo Belt (e.g., Alkmim et al., 2006; Pedrosa-Soares and Alkmin, 2011) (Figure 1E). With the final amalgamation of India to Australia–East Antarctica (e.g., Meert, 2003; Collins and Pisarevsky, 2005), the Pan-African orogeny ended. The polyphase assembly of the Gondwana supercontinent during the East Africa, Brasiliano, Kuungan and Damaran orogenic events thus extended from about 1000 Ma to at least the end of the Cambrian (~540 Ma to 490 Ma; Porada, 1989; Stanistreet et al., 1991; Meert, 2003; Begg et al., 2009; Nascimento et al., 2016).
Neoproterozoic stratigraphy in Namibia and DRC

The West Congo Supergroup rests unconformably on the ~2.1 Ga polymetamorphic Kimezian basement. It consists of up to 10 km thick siliciclastic and carbonate sequences with decreasing regional metamorphism from amphibolite facies in the west, through to unmetamorphosed rocks in the east (Frimmel et al., 2006). The metamorphosed rocks formed in the aulacogen thrust-and-fold belt, whereas the unmetamorphosed units represent deposition in the foreland basin. In Namibia, the Damara Supergroup is up to 14 km thick and consists of greenschist facies siliciclastics and carbonates deposited on a polymetamorphic Palaeoproterozoic basement.

The Neoproterozoic sedimentary successions in the West Congo and Damara belts are remarkably similar (Figure 2). Both record a long-lived initial rift - between ~900-750 Ma for the West Congo Supergroup (Tack et al., 2001; Frimmel et al., 2006), and between 770-750 Ma for the Damara Supergroup (McChesney et al., 2012; Miller, 2013), followed by a passive margin including carbonate platform deposits, and final continental collision between the Rio de la Plata and C-SF cratons approximately between 600 to 550 Ma (Merdith et al., 2017). Rift deposition is generally recorded by continental and rift-related volcano-sedimentary rocks. These are overlain by fluvio-deltaic siliciclastic and marine carbonates deposited on a passive margin. Continental collision and foreland basin deposition are recorded in the red bed facies of the 580-535 Ma Mulden Group in Namibia (Clauer and Kröner, 1979; Hedberg, 1979; Miller, 2008; Germs et al., 2009) and in the 566-490 Ma Mpioka Subgroup in DRC and Angola (Frimmel et al., 2006; Monié et al., 2012) (Figure 2).

In the West Congo Supergroup, up to two diamicite units, the Lower Diamictite Formation and the Upper Diamictite Formation (Lepersonne, 1951) have been interpreted, respectively,
as Sturtian (U–Pb age on baddeleyite single-grains: 694 ± 4 Ma; Straathof, 2011) and
Marinoan in age (Frimmel et al., 2006; Tait et al., 2011). In Namibia, glacial diamictites and
associated cap carbonates occur at the base of the Abenab (Sturtian) and Tsumeb (Marinoan)
subgroups, the Varianto and Ghaub formations respectively (Figure 2). The maximum age of
the Varianto Formation is 746 ± 2 Ma based on U-Pb ages in a tuff of the Nauport Formation
west of the Otavi Montainland (Hoffman et al., 1994; Hoffmann and Prave, 1996.). A coeval
depositional age of 760 ± 1 Ma was obtained from zircon grains (U-Pb TIMS) in a tuff of the
Devede Formation (Ombombo Subgroup) in the Summas Mountains (Halverson et al., 2005).
The Marinoan-equivalent Ghaub Formation yielded U-Pb zircon ages between 639.3 ± 0.3
Ma and 635 ± 1.2 Ma, based on zircon grains of an ash layer in the Ghaub Formation in
northwestern and south-central Namibia respectively (Hoffman et al., 2004; Prave et al.,
2016). An age of 635.2 ± 0.6 Ma obtained from an ash bed in the basinal equivalent of the
Ghaub Formation in south-central Namibia constrains the top of the Ghaub Formation (Prave
et al., 2016).
Our study will focus on the open-marine to lagoonal carbonates of the Hüttenberg Formation
(Tsumeb Subgroup) and the stromatolitic and oolitic C5 Formation of the Lukala Subgroup in
Namibia and DRC, respectively. The Hüttenberg Formation is constrained by the
stratigraphically-equivalent Kuiseb Formation in south-central Namibia, which yielded U-Pb
detrital zircon ages between 606 ± 24 Ma and 587 ± 9 Ma (Foster et al., 2015). 40Ar-39Ar
metamorphic ages of 590 Ma were obtained in the Kuiseb Formation in the Austerlitz
area (Lehmann et al., 2016). The C5 Formation is constrained between ~575 Ma and 566 ± 42
Ma, based on 87Sr/86Sr ratios in carbonate rocks of the underlying C4 Formation (Poidevin,
2007) and 40Ar-39Ar metamorphic ages obtained in the Mpioka Subgroup (Frimmel et al.,
2006) respectively. Recently, the age of the C5 Formation was refined between 575 and 540
Ma based on new chemostratigraphic and biostratigraphic data (Delpomdor et al., 2018).
This study is based on detailed facies descriptions and petrographic analyses of the Hüttenberg and C5 formations (Figure 3A). Six cores and two outcrop sections around the towns of Tsumeb and Abenab (Namibia) (Figure 3B) and two cores from Bamba Kilenda village (Figure 3C), located 150 km southwest of Kinshasa (DRC) are described in detail. Outcrop sections are located in the Tsumeb mine and west of Tsumeb along the B1 Road (Figures 3C and 4). Cores were sampled at the Tsumeb Mine (core S#66), Vogelsang 284 Farm (core MJNM#5-10), Guinab Farm (core MJNM#6-9), and Bombay Farm (core MJNM#12) located to the northwest of Abenab (Figures 3C and 5). In addition, two cores (Gx6c and GN7/9a) from the northern side of the Bamba Kilenda anticline were sampled at the Royal Museum for Central Africa, Belgium (Figures 3B and 6). A total of 406 samples encompassing the T7 and T8 Hüttenberg Formation in Namibia, and the C5 Lukala Formation in DRC were collected at intervals of approximately ~5 m and ~50 cm respectively. Drawings from photographic sketches are used to detail the geometry and internal sedimentary structures of beds.

Forty-eight samples were selected for whole rock carbon isotopic analyses. Carbonate powders were reacted with 100% phosphoric acid (density >1.9, Wachter and Hayes, 1985) at 75 °C using a Kiel III online carbonate preparation line connected to a ThermoFinnigan 252 mass spectrometer. All values are reported in per mil relative to V-PDB by assigning a $\delta^{13}$C value of +1.95‰ to NBS19. The reproducibility of $\delta^{13}$CV-PDB measurements is 0.04 ‰ (1σ).
Three samples were selected for Sr isotopes analyses. Sr values were measured using a VG54 multicollector mass spectrometer at the Université libre de Bruxelles (Belgium). The $^{87}\text{Sr}/^{86}\text{Sr}$ values were normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$.

**Stratigraphic framework of the studied successions**

**Hüttenberg Formation, Namibia**

The thickness of the Hüttenberg Formation is approximately 900 m (Porada, 1983). The lower part of the Hüttenberg Formation consists of up to 15 m-thick, light to dark grey-blue coloured, finely bedded shaley and laminar dolostone with *Conophyton*-type stromatolite, dolarenite, cherts and local breccia (Figure 4A).

The middle part of the Hüttenberg Formation contains, from base to top, (1) yellow to brown dolomitic shale with dark chert, (2) dark blue-grey laminar limestone, locally dolomitic, (3) yellow to brown dolomitic shales overlain by dark grey dolostone with breccia and brown shale interbeds, and (4) light blue-grey dolostone with white bluish nodules of anhydrite (Figure 4B). The uppermost part of this unit contains shallowing-upward sequences of dark grey dolostone, passing to grey planar to wavy laminar dolostone, overlain by blue-grey oolitic dolostone, often silicified, with planar and crossed laminations. Beds of blue-grey medium- to coarse-grained dolarenites and interbeds of dark cherts are also present.

The upper part of the Hüttenberg Formation is up to 250 m-thick and dominated by pale to dark blue-grey bedded laminar dolomitic limestone and dolostone interbedded with red to yellow dolomitic shale, blue-grey impure shaley limestone, and blue-grey oolitic limestone. Breccia and blue-grey calcarenite are also common (Figure 4C). Up to 9 m-thick evaporite beds with nodules of anhydrite and gypsum are locally observed (Kamona and Günzel, 2007).
The top of the Hüttenberg Formation consists of up to 200 m-thick pale greenish/brownish to
dark grey massive to laminar dolomitic limestone with interbeds of reddish to greenish-yellow
dolomitic shale, locally dark-grey silicified oolitic limestone, passing to pale brownish to dark
grey fine- to medium-grained dolostone interlayered by reddish brown dolomitic shale
(Figures 5A-E). Horizons and nodules of dark chert and white talc are also common. Massive
dolerite 0.70 m in thickness locally intrudes this unit (Figure 5D).

**C5 Formation, Lukala Subgroup, DRC**

The C5 Formation (estimated thickness between 150 m and 300 m; Lepersonne, 1973) is
divided, from the oldest to youngest, into C5a, C5b and upper C5b members. The C5a
member consists of 20-40 m-thick light grey lime conglomerate and breccia, light- to dark-
colored oolitic limestone and dolomitized limestone with cyanobacterial mats, evaporitic
(anhydrite after gypsum) and chert horizons.

The C5b Member is an approximately 40 m-thick dominant dark greenish to dark grey
massive to laminar limestone, often dolomitic. It locally contains small-scale LLH-type
stromatolites, and cm- to dm-thick well sorted dark grey to dark oolitic limestone including
*Obruchevella parva* in the nucleus, e.g., the “Kisantu Oolite”, which is locally silicified
(Figures 6A-B). Low-angle cross-laminations, rare ripples, erosional gutter casts and
desiccation cracks are present. Dark grey lime mudstone with whitish nodules of calcite
pseudomorphs of anhydrite and gypsum, yellow to reddish brown hardgrounds and
desiccation crack surfaces are associated. Filamentous cyanobacterium *Obruchevella parva*
was identified in the “Kisantu Oolite” in the stratigraphic-equivalent SCIII Formation in the
Republic of Congo (RC) (see Alvarez et al., 1995).
The overlying upper C5b Member is subdivided into C5b1 and C5b2 submembers (Lepersonne, 1973). The C5b1 submember, locally 95-135 m-thick, consists of approximately 40 m of light to dark greyish laminar to nodular dolomitic limestone, locally dolostone, with frequent ripples, yellow to reddish brown hardgrounds, desiccation cracks and calcretes. It is interbedded with reddish to dark grey dolomitic shale, and dark grey lime mudstone (Figure 6B). Nodules of calcite pseudomorphs of anhydrite and gypsum are common in this submember.

The C5b2 submember comprises 30-50 m-thick light greyish to whitish dolomitic limestone including cm-thick beds of silicified oolites, locally with talc. In the study area, it was eroded by the overlying Mpioka Subgroup and was not investigated in detail.

**Lithofacies and microfacies associations**

Twelve microfacies (MF1 to MF12) are recognized from outcrop and core sections and thin-section examination in the T7-T8 Hüttenberg and C5 formations. Lithology, sedimentary structures and textures, and fossil contents allow a grouping into nine lithofacies associations, LFA-H1 to LFA-H4 and LFA-C1 to LFA-C5 for the Hüttenberg and C5 formations respectively. Lithofacies associations and microfacies are summarized in Table 1, and shown in Figures 4-6.

**Hüttenberg Formation (Namibia)**

**Lithofacies association H1 (LFA-H1)**

Lithofacies association H1 only includes argillaceous (dolo)mudstone (MF1). In outcrop and core sections, LFA-H1 is dark blue-grey, microcrystalline and commonly dolomitic, with
argillaceous seams and stylolites. With increasing degree of dolomitization, the lithofacies may grade into medium to coarse grained dolomitic calcarenite and dolarenite. The massive micritic matrix (4-15 µm in size) is recrystallized to neomorphic microspar (15-20 µm in size) (Plate 1A). The dolomitic microfacies is composed of medium to coarse crystalline euhedral to anhedral dolomitic rhombs (50-100 µm in size) with rare intercrystalline clay seams. Silt- to sand-sized grains of quartz (>10% wt.), feldspars (>5% wt.) and micas (>20% wt.) are observed. No sedimentary structures were observed in this microfacies.

LFA-H1 is interpreted as low-energy lime muds deposited in a subtidal open-marine environment with detrital contributions. The absence of evaporites excludes protected conditions like lagoons. An open lagoon connected to the open sea via tidal inlets and with normal salinity is unlikely due to the low variety of sediment types and the absence of distinct tidal features.

**Lithofacies association H2 (LFA-H2)**

Lithofacies association 2 contains laminated (dolo)mudstone (MF2) and calcimicrobial (dolo)bindstone (MF3). The former consists of millimeter-scale laterally continuous light to dark brown, planar to wispy parallel, thin- to non-laminated mudstone. The matrix of the thin- to non-laminated mudstone is composed of fine micrite (5-10 µm in size) (Plate 1B), replaced by a neomorphic microspar (15-30 µm in size). Dolomitization is fairly common. The contact between the laminations is gradual.

Calcimicrobial bindstone (MF3) consists of submillimetric-scale, irregular and continuous, thin planar to wavy parallel microbial tubular filaments in a dark brown micrite matrix. Locally, the microfacies shows a closely-packed texture of randomly oriented tubular filaments and clumps of cyanobacteria micro-organisms. The filaments are dominantly non-
branched, non-septate, discrete tubules with a diameter between 50 µm and 500 µm (Plate 1C). Tubules with a diameter between 5 µm and 20 µm display dark-colored micritic walls (4-8 µm of thickness) often filled with equant sparry crystals (10-20 µm in size). Clumps are irregular and elongate, and form ellipsoid patches rimmed by a diffuse dark-colored micrite. Clumps rarely contain discrete remnants of tubular filaments. With increasing degree of dolomitization, the matrix shows fine crystalline euhedral to anhedral dolomitic rhombs (4-20 µm in size) in equigranular mosaic fabrics. Swallowtail twins, platy rectangular laths and nodules filled by calcite, replacing gypsum and anhydrite, are fairly common in these both microfacies. SiIlt- to sand-sized grains of quartz (>5% wt.), feldspars (>5% wt.) and micas (>2% wt.) were observed. Microfacies 2 and 3 are interpreted to have accumulated in low to moderate energy environments in the photic zone, which facilitated the seasonal carbonate production by cyanobacteria (Gerdes et al., 1994). Locally, the cyanobacteria formed small-scale calcimicrobial biostromes that are common on a carbonate mid-ramp setting (Turner et al., 2000).

Lithofacies association H3 (LFA-H3)

Two microfacies, peloidal (dolo)wackestone-(dolo)packstone (MF4) and stromatolitic (dolo)boundstone (MF5) form lithofacies association 3. In outcrop and core sections, MF4 only occurs in the T8 unit of the Hüttenberg Formation. Stromatolites of LLH-type, and locally spheroidal structures, Conophyton stromatolites are identified in this lithofacies. In thin section, MF4 consists of silt- to sand-sized irregular micritic peloids, locally cemented by radiaxial spar (Plate 1D), in a fine microcrystalline micritic matrix. The microfacies is characterized by abundant irregular pseudo-fenestrae, filled by an equant calcite cements.
MF5 displays thin sub-millimetric-scale, irregular, horizons of stromatolitic mats and clumps of cyanobacterial micro-organisms in a micritic to microsparitic matrix. Stromatolitic mats are planar to wavy and consist of dark micritic laminae up to 50 µm in thickness. The grumeaux consist of irregular and dark micritic rounded patches of stromatolites up 300 µm in size (Plate 1E), often filled by equant calcite cements (up to 50 µm in size). This microfacies locally shows vugs, veins, and desiccation cracks filled by bladed calcite cements associated with botryoidal and radiaxial cements. Both microfacies contain silt-to-sand-sized grains of quartz (10 to 50 µm of size, >2% wt.), fine-grained pyrites (less than 10 µm of diameter, >5% wt.) and remnant of tubular filaments are observed. The lithofacies association 3 is variably dolomitized, forming dolomudstone and dolorenite, with original textures obscured in outcrop and core sections, but commonly visible in thin sections.

The lithofacies association 3 corresponds to stromatolitic pinnacles in low- to moderate-energy conditions. Similar lithofacies have been described in the Neoproterozoic sedimentary successions from Canada (Batten et al., 2004; Thomson et al., 2014). Peloids formed the base of the stromatolitic buildups through the encrustations of micrite (probable aragonite mud) around cyanobacteria or as decomposition products of various algae (Flügel, 2010). The occurrence of pseudo-fenestrae associated with subspherical fenestrae suggests a shallow near-coastal peritidal environment (Flügel, 2010). Botryoidal cements are usually marine, and are common in cavities of reefs and in steep seaward dipping slopes (James and Ginsburg 1979).

**Lithofacies association H4 (LFA-H4)**

Lithofacies association 4 only includes oolitic (dolo)packstone-(dolo)grainstone (MF6). The microfacies dispays light blue-grey, medium- to well-sorted calcarenites and dolarenites with
indistinct cross laminations. In thin sections, MF6 consists of 1-2 mm-thick layers of medium- to well-sorted (dolomitized) oolitic packstone-grainstone (Plates 1F-H). The oolites occur either in a tightly packed dark brown lime matrix (packstone) or in coarse-crystalline lighter-coloured drusy sparry cements (grainstone). Sedimentary structures include wedge-shaped planar or trough cross laminations. The oolites are predominantly spherical to ovoid with a dark microcrystalline micritic fabric in the cortex. Alternatively, they consist of concentric tangential grains, or are grouped in coarse-grained grapestones (up to 1 mm). These latter are moderately elongated, flattened and stretched. Silicified yellow-colored oolites are locally observed. Associated with oolites, coalescent flattened peloids, debris of probable cyanobacterial mats (microbial chips) and vertical desiccation cracks are also observed.

In the Hüttenberg Formation, oolites represent a beach-barrier island environment. Trough cross-laminations indicate deposition in high-energy environments such as sandy carbonate shoals. Concentric oolites are common of high-energy in shorefaces and shoals (Burchette and Wright, 1992). Oolites and microbial chips result from reworking of fore- to back-barrier sediments (e.g., muds, cyanobacterial mats) by fair-weather waves, storms and/or tides.

**C5 Formation (DRC)**

**Lithofacies association C1 (LFA-C1)**

This lithofacies association includes argillaceous mudstone (MF7) and laminated mudstone (MF8). Argillaceous mudstones (MF7) consist of dark-grey, locally pale pinkish, massive limestone with thin argillaceous seams and stylolites. In thin section, the microfacies is characterized by a fine micritic matrix (Plates 1H-I), locally neomorphosed to microspar (15-20 µm in size). Where dolomitized, the matrix displays fine-grained hypidio- to xenotopic
dolomitic rhombs (5-10 µm in size). Wispy microbial mats, microbial chips, and isolated peloids, are also present observed. Mudstones (MF8) consist of laterally continuous dark grey, planar to wavy parallel, thin laminated limestone. Oblique and cross-laminations are also present. The laminations display dark brown micrite (up to 10 µm in size), locally with peloidal fabric (Plates II-J). The matrix is partially neomorphosed to microspar (15-30 µm in size) or, replaced by idio- to hypidiotopic dolomicrosparitic crystals (up to 50 µm in size).

This lithofacies association contains silt-sized quartz, irregular and flattened peloids (up to 20 µm of diameter), randomly oriented swallowtail twins and platy rectangular laths of replaced gypsum, stratabound nodules and enterolithic anhydrite replaced by calcite cements.

The argillaceous mudstone (MF7) is interpreted as low-energy lime muds deposited in subtidal environments. The occurrence of anhydrite pseudomorphs points to protected lagoonal conditions, probably barred by sandy shoals and reefs. The association with the laminated mudstone (MF8) is also inferred to low energy inter- to supratidal lagoonal settings colonized by cyanobacterial mats periodically reworked by intertidal currents. Arid conditions are recorded by the precipitation of stratabound gypsum and anhydrite.

**Lithofacies association C2 (LFA-C2)**

Lithofacies association C2 is abundant in the C5b Member of the C5 Formation and consists of dark coarse grained, well-sorted, crossed laminated oolitic grainstone (MF9). Grainstone contains tightly-packed spheroidal to ellipsoidal siliceous ooids and pisoids up to 50 µm in diameter (Plates 1K-L) within wedge-shaped planar or low angle crossed laminations. Oolites are dominantly composed of multiple-coated and tangentially arranged laminations with either calcite or quartz in the cortex. Intergranular pores are occluded either by lighter-
coloured drusy sparry calcite cements, or by micro- to megacrystalline quartz cements. Desiccation cracks and rare lamellar and meniscus sparry cements are present. This lithofacies association represents oolitic sands deposited on beach separating the supratidal mudflat and sabhka sediments from the evaporitic lagoon. Our interpretation is similar to the depositional model of the stratigraphically-equivalent oolitic shoals in RC (Alvarez, 1995). Coated grains are well sorted by tidal currents during the abrasion, reworking and transport of lagoonal sediments. This grainstone lithofacies is also periodically subjected to subaerial exposures with desiccation cracks.

**Lithofacies association C3 (LFA-C3)**

Lithofacies association C3 consists of microbi ally laminated mudstone (MF10). MF 10 is dark gray, submillimetric, irregular and continuous, thin microbi ally laminated, planar and wavy parallel limestone. In thin section, the microfacies displays dark brown microcrystalline micritic laminations in light dark gray-brown micritic or neomorphosed microsparitic matrix (Plate 1M). Fenestrae characterized by small spar-filled cavities and larger irregular voids are present. Platy rectangular laths of replaced gypsum, stratabound nodules and enterolitic structures filled by calcite pseudomorphs of anhydrite are also visible. Subvertical desiccation cracks, locally forming *in-situ* breccias, filled by sparry cements cut-across the microbial laminations. The lithofacies association C3 represents shallow inter- to supratidal settings in evaporitic environments. Fenestrae and desiccation cracks indicate episodic subaerial exposures in intertidal settings (Grotzinger, 1986; Pratt et al., 1992).

**Lithofacies association C4 (LFA-C4)**
Lithofacies association C4 only includes the evaporitic dolomudstone microfacies (MF11). This microfacies is a mud-supported dark-grey dolomitic limestone dominantly composed of brownish to bluish white nodular anhydrite and interbeds of anhydrite. Anhydrite is commonly replaced by a light drusy sparry cement, but microcrystals of anhydrite are occluded in these cements. Various types of gypsum crystals such as lenticular, lozenge-shaped, swallowtail twinned, and platy rectangular forms are fairly common (Plates 1M-O). Small-sized nodules and chicken-wire structure show loosely packed aggregates of tiny platy rectangular laths and stellate crystals (Plate 1N). Locally, 1-2 cm-thick layers of massive anhydrites are mixed with dolomudstone. The matrix is composed of equigranular xenotopic to hypidiotopic dolomitic crystals (5-15 µm in size) in non-planar fabrics. Desiccation cracks (20-200 µm of width) filled by drusy sparry cements, and hardgrounds are also present. This lithofacies association represents supratidal evaporitic environments. Such sediments are encountered in the recent shallow peritidal shelf and coastal sabkha of Abu Dhabi (Shearman, 1978). Lenticular, swallowtail twins and lath patterns are indicative of saline intertidal diagenesis (Cadwell, 1976) while nodules and chicken-wire structures are common in sabkha and are the result of the replacement of gypsum by anhydrite crystals in soft sediments by capillarity-dehydration processes (Kinsman, 1969). Periodical emersions were recorded and form polygonal desiccation cracks or non-deposition throughout inter- and supratidal beachrocks (see lithofacies association C5 for explanation).

**Lithofacies association C5 (LFA-C5)**

In the C5 Formation, the lithofacies association C5 is rare, and only includes the calcrete microfacies (MF12). MF12 consists of dark, rarely yellowish-orange, millimetric-thick crusts
of slightly undulated laminations, and in-situ brecciation of dolomitized limestone. Abundant desiccation cracks are also common. In thin section, the microfacies shows light grey brown fine- to medium-grained dolomitic mudstone, locally dolomitized wackestone with coated grains, composed of oolites and peloids, with dense dolomicrite concentrated into crusts (Plate 10). Veins of sparite form an in-situ brecciation. Sand-sized dense dolomicritic ‘glaebules’ and dolomicrite coatings are also associated with this microfacies. The matrix exhibits hypidiotopic dolomitic crystals (20 µm in size). Rare laminations are planar parallel to crossed. Calcite pseudomorphs after anhydrite (rosettes, laths, or fibrous replaced gypsum) are fairly common. Meniscus sparry cements are observed on the rims of coated grains. This lithofacies association is interpreted as near-surface soil horizons or paleosoils, formed by the accumulation of CaCO$_3$ and the oxidation of beachrock surfaces by iron hydroxides in semi-arid climate conditions under sparse rainfall (Adatte et al., 2005). Occurrences of evaporites and brecciation indicate that the sediment was affected by desiccation, emersion, and periods of dissolution. Such processes are common in supratidal and continental environments. The presence of meniscus sparry cements indicates vadose conditions.

**Depositional framework interpretation**

The lithofacies associations (LFA-H1 to LFA-H4 and LFAC1 to LFA-C5) of the Hüttenberg and C5 successions integrate the variations in sea level, energy and salinity in the carbonate ramp. In both the Hüttenberg and C5 formations, lithofacies associations are arranged in up to 4 m-thick depositional cycles showing an upsection trend from marine to restricted deposition, which is broadly followed by an upsection increase in energy level (Figure 7). The lithofacies associations comprise six main belts described here from a distal to proximal gradient recording the different levels of the hydrodynamic energy: (i) microbial ‘mounds’,
(ii) stromatolitic reefs, (iii) ooid-barrier shoals, (iv) evaporitic brackish lagoons, (v) beaches and (vi) coastal sabkas (Figure 8). The type-1 cycle is characterized by a LFA-H1 to LFA-H4 succession of lithofacies associations, while the type-2 cycle contains a LFA-C1 to LFA-C5 succession.

The gradual transitions between lithofacies associations and the general increase of depositional energy upsection, suggest that both formations represent deposition in a mid- to inner carbonate homoclinal ramp. A beach-barrier/island-lagoon model could be applied to both successions, due to the moderate to high wave energy, a relatively high tidal range estimated at ~1.8 m for the C5 Formation (see Delpomdor et al., 2018), a high carbonate sand production, and the high contents of evaporites. An oolitic sand shoal-barrier separated an open-marine sea with stromatolitic pinnacle reefs from a back-reef carbonate-evaporitic lagoon bordered by a coastal sabkha plain (Figure 8).

The assemblage of lithofacies associations LFA-H1 and LFA–H2 form the lower domain of the middle carbonate ramp, and records low- to moderate-energy open-marine conditions as revealed by the lime mud content and the microbial patch mounds deposited on gently dipping slopes. Cyanobacterial micro-organisms were associated with outer ramp LLH-type stromatolitic buildups forming small-scale mounds and pinnacles (LFA-H3). These stromatolites grew in moderate- to high-energy shallow waters around an active wave base.

The ooid shoal lithofacies (LFA-H4) form a barrier island, and represent high-energy sediments related to tidal and wave agitation. The ooids indicate 'warmer' and possibly aragonite-saturated waters, preferentially dolomitized by brines percolating from the lagoonal and evaporitic environments during dry to arid climatic episodes (van Smeerdijik Hood and Wallace, 2018). The middle-inner carbonate ramp profile and its geometry are observed on homoclinal shelf margins of other Neoproterozoic successions (Batten et al., 2004: Cozzi et al., 2004; Thomson et al., 2014).
The Hüttenberg units of our study were deposited in the post-rift Khomas sea along the southern margin of the Congo Craton. They represent the development of a shallow-water carbonate epicontinental platform (Stanistreet et al., 1991; Kamona and Günzel, 2007).

However, the presence of dessication cracks and breccia indicates that during deposition, the sediment was periodically subjected to subaerial exposure. Locally, lagoonal sediments were affected by hypersaline conditions, with microbial mats, evaporites (horizons of 9-14 m of thickness) and cherts resulting (Kamona and Günzel, 2007). These conditions are confirmed by typical marine REE +Y signatures, and highly variable enrichment in $^{13}$C (reaching several plateaux of +8‰ to +12‰) due to elevated evaporation rates in a restricted basin (Frimmel, 2009, 2010).

In the C5 Lukala Formation, the lagoonal belt shows a typical blackened dolomitized limestone lithofacies association (LFA-C1 to –C4) with a relatively high organic content suggesting possible periods of dysoxia/anoxia in the lagoon. The reducing waters were followed by well-oxygenated waters, which facilitated the development of benthic cyanobacterial mats in the nearshore zones of the lagoon. The coastal shoreline zone (LFA-C3) was marked by waves, tides and elevated salinity. Off-shore sand bars on a beach-strandplain belt were probably dominated by high wave energy and low tidal range as shown by ripples, cross laminations, and reworking and transport of cyanobacteria fragments living in the foreshore and backshore environments. Beachrock formed due to rapid cementation of sand-sized grains by aragonite and Mg-calcite crystals growing in the interparticular spaces. Beachrock is a common feature of low-latitude warm-water beaches in tropical and temperate environments and formed during cessation of sedimentation or periods of low sedimentation rate (Scoffin and Stoddard, 1983). The sabkha evaporites, dolomitization, and caliche crusts (LFA-C4 to -C5) can be used as paleoclimatic markers of semi-arid normally low-latitude deposition. The evaporites, dolomitization, and caliche crusts (LFA-C4 to -C5), point to an
arid climate of deposition instead. Extensive dolomitization, locally capped by caliche surfaces at the top of evaporitic cycles, occurred between the coastal and the reefal zones. The upper parts of sections of the carbonate-evaporitic lagoon were seasonally subjected to precipitation with formation of caliche surfaces, containing vadose pisoids, pseudo-peloids, and breccias.

The distribution of open-marine type-1 cycle of the Hüttenberg Formation follows a thin peritidal cycle with an average cycle thickness of approximately 4 m (in this paper), while the type-2 cycle of the C5 Formation shows an average thickness of ~1.8 m (Delpomdor et al., 2018). Such thicknesses are frequent in peritidal environments (Catuneanu et al., 2011; Franseen and Byrnes, 2012; Delpomdor et al., 2015). The open-marine type-1 cycle of the Hüttenberg Formation preludes the lagoonal and near-shore type-2 cycle of the C5 Formation, and locally present in the T8 unit of the Hüttenberg Formation. Although the Hüttenberg Formation and the C5 Formation were deposited in two distinct basins on the southwestern and western margin of the C-SF cratons, there are similar patterns of lithofacies associations that reflect similar deposition on passive margins during the global post-Marinoan sea-level transgression.

**Carbon and strontium isotopes**

The carbon and strontium isotopic data for the C5 Formation (DRC) are shown in Table 2. Analysis of major and trace elements demonstrate that the samples retained their original marine isotope signature (Delpomdor and Préat, 2013). Carbon isotope data for the Hüttenberg Formation from a previous study on Tsumeb core S86A (Kaufman et al., 2010) are compared with our results for stratigraphic correlation.
The C5a/C5b boundary is marked by a positive shift in δ^{13}C values from +1.5‰ to +7.5‰, followed by an upwards-decrease in δ^{13}C values from +7.5‰ to +1.3‰. A second positive shift occurs in the middle C5b, with δ^{13}C values varying from +1.3‰ to +10.8‰, followed by a significant upwards-decreasing of δ^{13}C until +3.1‰. The C5b/upper C5b boundary is marked by positive isotopic shift in δ^{13}C from +3.1‰ to +5.6‰ directly overlain by a rapid return to negative isotopic shift in δ^{13}C around +1.7‰. The upper C5b Formation displays higher δ^{13}C values than the C5a and C5b formations with a mean value ranging around +6.2‰. At the top of the succession δ^{13}C values fall sharply to near +3.5‰, just before being truncated by the molasse of the Mpioka Subgroup in this part of the DRC. One sample of the C5b Formation has a strontium isotope ratio of 0.7081, while ⁸⁷Sr/⁸⁶Sr ratios in the upper C5b Formation range between 0.7084 and 0.7090 (n = 2). Overall, ⁸⁷Sr/⁸⁶Sr ratios are altered by diagenetic fluids directly after deposition, as evidenced by the low Sr concentrations above the cut-off of 300 ppm (Halverson et al., 2007), and cannot therefore be used as a proxy for correlation (Delpomdor et al., 2018). However, samples from the same unit published by Frimmel et al. (2006), close of the cut-off of 300 ppm plot in the same ⁸⁷Sr/⁸⁶Sr ranges (0.7074-0.7075) and are considered as unaltered samples, representative of the seawater composition.

The Hüttenberg Formation carbonates revealed a significantly higher positive carbon isotope excursion than at any other time in the Neoproterozoic Era (Kaufman et al., 2010). The lower part of the Hüttenberg Formation shows a range of values between +8‰ and +10‰. The middle and upper parts are marked by isotopic shifts of δ^{13}C values from +12‰ to +4‰ and from +10‰ to +2‰ respectively. The lowest δ^{13}C values between +0‰ and +2‰ are encountered in the middle part of this unit. ⁸⁷Sr/⁸⁶Sr ratios in the Hüttenberg Formation range between 0.7076 and 0.7086 (n = 2) with Sr concentrations between 60 and 1220 ppm (n = 2) (Frimmel et al., 1996).
The δ13C data of both Hüttenberg and C5 formations are significant with the carbon isotopic values published by Frimmel et al. (1996) and Halverson et al. (2005), in the same range.

**Stratigraphic correlations**

Current regional correlations of Cryogenian and Ediacaran glaciogenic successions in central east Brazil, northwestern Namibia and west central DRC rely on chemostратigraphic and radiometric age constraints (Figure 10; Pedrosa-Soares et al., 2008; Kaufman et al., 2010; Tait et al., 2011; Caxito et al., 2012; Cailteux et al., 2015). Numerous correlations between the carbonate successions of the Bambuí Group (central east Brazil; ~750–540 Ma in age) and the West Congo Supergroup (west central DRC) have been suggested (Alkmim and Martins-Neto, 2012; Caxito et al., 2012; Cailteux et al., 2015) but are hampered by lack of precise radiometric dating of both successions (Santos et al., 2000; Caxito et al., 2012; Paula-Santos et al., 2017). Both sedimentary successions are considered as coeval with the Damara Supergroup (Cailteux et al., 2015). Based on lithostratigraphic and radiometric data, the Tsumeb Subgroup in Namibia and the Gombela Subgroup of the Central Africa Copperbelt (CAC) in DRC and Zambia were considered as coeval (Miller, 2013). The Tsumeb Subgroup succession is constrained by an U-Pb zircon age of 635 ± 1.2 Ma on an ash layer interbed in the Ghaub Formation (Hoffmann et al., 2004), and U-Pb detrital zircon ages on metasediments between 606 ± 24 Ma and 587 ± 9 Ma in the Kuiseb Formation (Foster et al., 2015; Lehmann et al., 2016), considered as stratigraphic-equivalent with the Hüttenberg Formation (Miller, 2008). The youngest age is confirmed by 40Ar-39Ar metamorphic ages of 590 Ma obtained in the Kuiseb Formation (Lehmann et al., 2016). A minimum deposition age for the top of the Swakop Group in Northern Zone of Namibia, intruding the Karibib and Kuiseb formations, is constrained by granite and metamorphic age determinations of ~585-
570 Ma (Bergemann et al., 2014; Milani et al., 2014; Forster et al., 2015). In the CAC, the oldest metamorphic ages are 592 ± 22 Ma (U–Pb monazite) and 585.8 ± 0.8 Ma Ar–Ar plateau age for biotite (Rainaud et al., 2005). Recently, Cailteux et al. (2015) correlated the lower part of the Lukala Subgroup (C1-C3 formations) of the West Congo Supergroup with the Gombela Subgroup, which displays a strongly comparable sedimentary succession, in particular the similarity between the oolitic limestone of the Lubudi and C3 formations. However, this correlation is still debated due to the lack of chemostratigraphic and radiometric constraints.

In the absence of temporally significant fossils and radiometric constraints, carbon isotope stratigraphy was specifically applied to the correlation of carbonates above and below the Namibian “Marinoan-age” glacial deposits, e.g., Ghaub Formation (Kaufman et al., 1991). Composite carbon-isotope profiles spanning the inferred Marinoan and Pan-African deformation events in northwestern Namibia, west central DRC, and central east Brazil show two carbon-isotope trends. The first trend (arrow 1) is marked by a positive to negative shift in \( \delta^{13}C \) values in the dolostones of the Maleberg in Namibia and C1 formations in DRC, and the Pedro Leopoldo Member, lowermost unit of the Sete Lagoas Formation in Brazil (Santos et al., 2000; Halverson et al. 2005; Straathof, 2011; Caxito et al., 2012; Delpomdor and Préat, 2013; Cailteux et al., 2015; Paula-Santos et al., 2017). This isotopic “event” is followed by a positive excursion in \( \delta^{13}C \) values, which is marked by a rapid marine transgression as a result of extensional tectonic processes directly after the Marinoan-age glaciation event (Halverson et al., 2005; Delpomdor et al., 2016; Caxito et al., 2012; Paula-Santos et al., 2017). Such glaciations are recorded in the Ghaub Formation in Namibia, Jequitaí Formation in Brazil, and periglacial deposition in the Niari Formation in Gabon, stratigraphic-equivalent of the distal gravity deposited sediments in the Upper Diamictite Formation in DRC (Prian et al., 2009; Busfield and Le Heron, 2013; Uhlein et al. 2013, 2016; Delpomdor et al., 2016, 2017;
The second trend (arrow 2) is marked by a negative to positive excursion in δ¹³C values in the Elandshoek and Hüttenberg formations in Namibia, comparable to carbon-isotope values of the C4 and C5 formations in DRC and the upper part of the Sete Lagoas (Santa Lagoa Member) to Lagoa do Jacaré formations in Brazil (Kaufman et al., 1991, 2010; Frimmel et al., 1996; Santos et al., 2000; Halverson et al., 2005; Frimmel et al., 2006; Straathof, 2011; Caxito et al., 2012; Delpomdor and Préat, 2013; Cailteux et al., 2015; Paula-Santos et al., 2017; Delpomdor et al., 2018). The contact between the C3/C4 formations in DRC, as well as in the stratigraphic-equivalent SCI-SCII in the Republic of Congo (A.P.- Ackouala, 2018, pers. comm.), shows abrupt lithological changes and negative carbon-isotope shift related to a possible Gaskiers-age event (Cailteux et al., 2015; Delpomdor et al., 2018). The second carbon-isotope trend corresponds to a second marine transgression, which flooded the Damara, West Congo, and São Francisco basins in Namibia, DRC and Brazil respectively (Martins-Neto et al., 2001; Cailteux et al., 2015; Préat et al., 2011; Reis and Alkmim, 2015; Delpomdor et al., 2018). This transgression eventually gave rise to a restricted basin without an efficient mixing with external seawater. Because of the stagnant dysoxic to anoxic water columns the organic matter was preserved in the evaporitic shallower environments (e.g., the Hüttenberg, C5, and Lagoa do Jacaré formations). We suggest that the second marine transgression favoured regional-scale exchange with other basins accompanied by flora migration and development of benthic helicoidal cyanobacteria *Obruchevella parva* in the C5 Formation (Alvarez et al., 1995; Delpomdor et al., 2018) and *Cloudina* and *Corumbella* in the Sete Lagoas Formation (Warren et al., 2015), and unknown cyanobacterial organisms in the Hüttenberg Formation (this study). *Obruchevella parva* is commonly considered as an index fossil for the terminal Ediacaran (Yakschin and Luchinina, 1981) or Cambro-Ordovician (Reitlinger, 1959). *Cloudina* and *Corumbella* are considered as index fossils for the terminal Ediacaran (Warren et al., 2015).
et al., 2015), which is recently supported by maximum deposition ages (U-Pb zircon dating) of ~ 557 Ma for most of the Sete Lagoas Formation (Paula-Santos et al., 2015). Although the index fossil *Cloudina* is absent in the C5 and Hüttenberg formations, probably due to a later closure of the marine interconnection between the C-SF and Kalahari cratons, the abundance of cyanobacterial organisms might be considered as a coeval biological marker for stratigraphic correlations between the uppermost parts of the Sete Lagoas to Lagoa do Jacaré formations, and the C5 Formation (Cailteux et al., 2015; Delpomdor et al., 2018), thereby allowing the debatable Late Ediacaran age (e.g., 580-540 Ma) of the Hüttenberg Formation to be applied to the Sete Lagoas and Lagoa do Jacaré formations.

In this paper, $\delta^{13}$C values of the C5 and Lagoa do Jacaré carbonates are compared with the carbon isotope values from the Tsumeb core S86A, (Kaufman et al., 1991) (Figures 9 and 10), and the published data from Halverson et al. (2005). The C5 Formation shows seven upwards-increasing trends of $\delta^{13}$C that may be correlated to the lower and middle parts of the Hüttenberg Formation. A distinct negative shift of $\delta^{13}$C values at the top of the Hüttenberg Formation is currently not recognized at the top of the C5 Formation due to lack of data resulting from erosion by the Mpioka Subgroup (Figure 9). This negative $\delta^{13}$C shift can be correlated to the Gaskiers (580 Ma) or Moelv (560 Ma) isotope shifts linked to the Numees Formation diamictite in southern Namibia (Kaufman et al., 1991), or to the Basal Cambrian Isotope Excursion (BACE; see Alvaro et al., 2008). In Brazil, the Lagoa do Jacaré Formation shows comparable $\delta^{13}$C values, to the Hüttenberg and C5 formations (Figure 10).

All formations are overlain by molasse-type sediments related to the collision of the Rio de la Plata Craton with the C-SF cratons and closure of the Adamastor Ocean along the 575–540 Kaoko-Gariep-Araçuaí-West Congo belts (e.g. Frimmel and Frank, 1998; Frimmel et al., 2006; Konopásek et al., 2014; Merdith et al., 2017), and the closure of the Khomas Ocean
between C-SF and Kalahari cratons around 550 Ma with the development of the Damara-
Lufilian-Zambezi Orogen (e.g. Naydenov et al., 2014; Merdith et al., 2017).

Independent of the absolute ages, the similarity in chemostratigraphy, their similar
stratigraphic position, sedimentology and sea level evolution, suggest that Hüttenberg and C5
formations might be coeval deposits on the margins of the C-SF cratons. In this paper, we
consider the age of the C5 Formation, and its stratigraphic-equivalent Hüttenberg Formation,
as terminal Ediacaran (e.g., 580-540 Ma). However, the current knowledge of the depositional
ages of these sedimentary successions through the Damara and West Congo basins is very
limited which limits more precise prediction of stratigraphic correlations.

Conclusions

New descriptions and sedimentological study of key cores and outcrops in the Hüttenberg
Formation in northwestern Namibia show that this unit formed in an open-marine mid-inner
carbonate ramp setting with organic mounds, pinnacles and oolitic shoal-barrier islands. The
mid ramp includes shallow-water microbial and stromatolitic patch mounds and pinnacles,
respectively, formed on gentle slopes at the outer edges of the shelf on the southern margin of
the Congo-São Francisco cratons. Inner ramp deposits are composed of oolitic shoals and
lagoonal muds, locally subjected to hypersaline conditions, behind a wide gently sloping
shelf. Sedimentology establishes similar lithofacies associations in the C5 Formation of the
Democratic Republic of Congo, with four main belts recording different levels of
hydrodynamic energy following a distal to proximal gradient from: (i) an ooid-barrier shoal,
(ii) an evaporitic brackish lagoon, (iii) a beach, and finally (iv) a coastal sabkha.
The carbonate ramp represented by the Hüttenberg Formation is considered as regionally
correlative of the C5 carbonates. In term of geochronology, the Hüttenberg Formation is
constrained by U-Pb zircon ages of ~635 Ma and ~590 Ma in the Ghaub and Kuiseb formations in Central Namibia. Due to the lack of radiometric data in the Tsumeb Subgroup in northwestern Namibia, carbon-isotope stratigraphy was tentatively applied to the correlation as reference curves for worldwide carbonate successions (Halverson et al., 2005).

Two $\delta^{13}C$ trends were identified as the result of a marine transgression, interconnected with global extensional tectonic processes, directly after the Marinoan-age glaciation event. The first carbon-isotopic trend is marked by a strong negative anomaly in $\delta^{13}C$ values, followed by a negative to positive excursion, probably coeval with the Maieberg Formation in Namibia, the C1 to C3 formations (Kwilu unit) in DRC, and the lower part of the Sete Lagoas Formation (Pedro Leopoldo Member) in Brazil. A second negative to strongly positive excursion in $\delta^{13}C$ values is recognized in the Elandshoek-Hüttenberg succession in Namibia, comparable to the carbon-isotope values in the C4-C5 formations in DRC, and in the upper part of the Sete Lagoas (Santa Lagoa Member) and Lagoa do Jacaré formations in Brazil. This carbon-isotope excursion records a second marine transgression, which gave rise to regional-scale exchange with other basins accompanied by flora migration and development of Late Ediacaran benthic cyanobacterial micro-organisms, abundantly present in the Hüttenberg and C5 formations. The convergence of chemostratigraphic data and biostratigraphy suggest a Late Ediacaran age - e.g., 580-540 Ma - of deposition for the both Hüttenberg and C5 formations, comparable to the Lagoa do Jacaré Formation in Brazil.

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Table 1: Summary of lithofacies association characteristics of the Hüttenberg Formation (Namibia) and the C5 Formation (Democratic Republic of Congo).

Table 2: C-, O- and Sr-isotopic and elemental geochemical data.
Figures

**Figure 1:** Cartoon illustrating the Neoproterozoic palaeogeographic reconstruction of the Congo-São Francisco (C-SF) cratons (modified after Stanistreet et al. 1991; Alkmim et al. 2006). (A) Reworked 1.1 Ga-950 Ma Rodinia Supercontinent centered on the present-day Africa and South America continents. (B) Continental rifting at ~1 Ga. (C) Opening of the Khomas Ocean separating shelves on the C-SF and Kalahari continental margins. (D) Initial closure of the Adamastor Ocean, at ~720 Ma, as a consequence of the C-SF, Rio de la Plata, Kalahari interaction. (E) Pan-African-Brasiliano orogen on the Gondwana Supercontinent at ~540 Ma. Abbreviations: Craton - Am, Amazonia; RP, Rio de la Plata; WA, West Africa; Co, Congo; SF, São-Francisco; Ka, Kalahari, Ta, Tanzania block (Congo craton); AR, Arequipa; Ho, Hoggar; In, India; EAn, East Antarctica; Was, West Australia; NAs, North Australia; Ga, Gawler. Pan-African-Brasiliano orogens – RP, Rio Preto, BR, Brasiliano; SP, Sierra Pampeanas; WC, West Congo; KK, Kaoka; DA, Damara; GA, Gariep; LF, Lufilian; ZB, Zambezi; MO, Mozambique; SA, Saldania; CF, Cape Fold; RO, Ross; KA, Kanmatoo. Stars: C5 Formation in the Democratic Republic of Congo, Hüttenberg Formation in Namibia.

**Figure 2:** (A) Regional geological sketch map of the study area. (B) Geological map of the section Lukala-Mbanza Ngungu (after Cailteux et al., 2015). (C) Geological map of the Damara belt (after Kamona and Günzel, 2007). Location of the studied outcrops and core sections in yellow stars.

**Figure 3:** Lithostratigraphy and chronostratigraphy of the (A) Damara Supergroup and (B) the West Congo Supergroup (see text for discussion). New and previous terminology of the
West Congo Supergroup falls outside the scope of this paper but is briefly discussed in Kant-
Kabalu et al. (2016).

**Figure 4:** Detailed lithostratigraphy coupled with microfacies analyses. (A) Tsumeb Mine
(GPS coordinate: S19°14′07.80/E17°43′49.40). (B) Tsumeb town (GPS coordinate: S
19°15′60.60/E17°42′44.30). (C) S#6 drillcore (GPS coordinate: N304893/E76412).

**Figure 5:** Detailed lithostratigraphy coupled with microfacies analyses. (A) MJNM#5
drillcore, farm Vogelsang 284 (GPS coordinate: S19°10′00.86/E18°21′42.01). (B) MJNM#6
drillcore, farm Guinab 277 (GPS coordinate: S19°11′11.57/E18°22′48.53). (C) MJNM#9
drillcore, farm Guinab 277 (GPS coordinate: S19°10′10.46/E18°22′47.86) (D) MJNM#10
drillcore, farm Vogelsang 284 (GPS coordinate: S9°12′51.38/E17°57′28.12). (E) MJNM#12
drillcore, Farm Bombay 670 (GPS coordinate: S9°12′51.38/E17°57′28.12).

**Figure 6:** Detailed lithostratigraphy and lithology coupled with microfacies analyses and C
isotopes. (A) GX6c drillcore (RMCA serial number RG40421-40466). (B) GN7/9a drillcore
(RMCA serial number RG40178-40198).

**Figure 7:** Vertical changes of microfacies (MF1 to MF12) represented by type-1 and -2
cycles of open marine- to restricting-upward carbonate sequences. The type-1 cycle is
characterized by a LFA-H1 to LFA-H4 succession of complete cycles that begin with LFA-
H1, while the type-2 cycle contains a LFA-C1 to LFA-C5 succession that begin with LFA-C1
(see text for discussion).
Figure 8: Carbonate ramp geometry and facies distribution of the Hüttenberg Formation in Namibia and the C5 Formation in DRC. (A-C) Middle- to inner carbonate ramp of the Hüttenberg Formation. (A) Middle carbonate ramp of the Hüttenberg Formation with (dolo)mudstone (MF1-2) overlain by mounds and pinnacles of microbial and SH/LLH-type stromatolitic buildups (MF3-5). High-energy oolitic (dolo)packstone-grainstone (MF6) form barrier shoals. (B) Inner carbonate ramp of the Hüttenberg Formation exhibits a temporary emerged hypersaline lagoon with desiccation cracks and breccias (see MF10). (C-D) Inner carbonate-evaporite ramp of the C5 Formation. (C) Shoal-barrier and lagoonal ramp settings of the C5a Member (MF7-9). (D) Nearshore carbonate-evaporite ramp setting with beach and coastal sabkha plain (MF10-12).

Figure 9: Attempt at carbon-isotope correlation between the C5 carbonate rocks and the high-resolution $\delta^{13}C$ data from the Tsumeb core S86A drilled in the Hüttenberg Formation (data after Kaufman et al. 2010).

Figure 10: Composite carbon-isotope profiles and simplified stratigraphic columns spanning the inferred Marinoan and Pan-African deformation events in northwestern Namibia, west central DRC, and central east Brazil. The three sedimentary successions are marked by two marine transgressions, after the Marinoan-age glaciation. Two carbon-isotope trends show (i) a very negative anomaly, directly after the Marinoan glaciation, marked by the deposition of the Ghaub Formation in Namibia, Upper Diamictite Formation in DRC, and Carrancas/Jequitai formations in Brazil, (ii) a negative to positive excursion in $\delta^{13}C$ values in the Maieberg Formation in Namibia, comparable to the C1-C3 formations in DRC, and the lower part of the Sete Lagoas in Brazil, and (iii) a second negative to strong positive excursion in $\delta^{13}C$ values in the Elandshoek-Huttenberg formations in Namibia, comparable to
the C4-C5 formations in DRC, and the upper part of the Sete Lagoas Formation to the Lagoa do Jacaré Formation in Brazil. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are here indicative. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from Namibia: Frimmel et al. (1996) and Halverson et al. (2007); DRC: Frimmel et al. (2006), Poidevin (2007), and Delpomdor and Préat (2013); Brazil: Caxito et al. (2012) and Paula-Santos et al. (2015, 2017).

Plate

Plate 1: Microfacies analysis. (A) Homogeneous mudstone (MF1). (B) Planar to wispy parallel laminated mudstone (MF2). (C) Tightly-packed microbial tubular filaments in a bindstone texture (MF3). (D) Silt- to sand-sized peloidal wackestone/grainstone (MF4). (E) stromatolitic boundstone with fenestral fabric filled by equant calcite cements (MF5). (F) Tightly packed fine-grained concentric tangential to radial oolites in a packstone texture (MF6). (G) Reworked stromatoclasts in an oolitic grainstone cemented by calcite cements (MF6). (H) Thin-levels of oolitic and peloidal packstone (MF6) alternating with homogeneous mudstone (MF7). (I) Vertical desiccation crack in a homogeneous mudstone (MF7) capped by thin wavy parallel laminated mudstone (MF8). (J) Thin planar to oblique parallel microbial laminites. (K) Oolitic grainstone (MF9) in calcite cements. (L) Occurrence of helicoidal cyanobacteria, attributed to Obruchevella parva Reitlinger (1959), in the nucleus of oolites (‘Kisantu Oolite’, see Alvarez et al. 1995). (M) Alternations of planar to wavy parallel microbial laminites (MF10) and evaporitic mudstone (MF11). (N) Small-sized nodules showing loosely packed aggregates of tiny platy rectangular laths and stellate crystals (MF11). (O) Dolomitized lime mudstone (MF12) capped by evaporitic mudstone (MF11).
### Type-1 cycle - open marine

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<tr>
<th>Environment</th>
<th>Lithofacies association</th>
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<td>Intertidal shoal barrier</td>
<td>Oolitic (dolo)packstone/gravestone (MF6)</td>
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<td>Sub- to intertidal organic mounds</td>
<td>Stromatolitic (dolo)boundstone (MF5)</td>
<td>H3</td>
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<tr>
<td>and pinnacles</td>
<td>Peloidal (dolo)wackestone/packstone (MF4)</td>
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<tr>
<td>Shallow subtidal open-marine</td>
<td>Microbial (dolo)bindstone (MF3)</td>
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<td>Subtidal open-marine</td>
<td>Laminated (dolo)mudstone (MF2)</td>
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<td>Argillaceous (dolo)mudstone (MF1)</td>
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**Note:** Thickness of each environment is indicated.

### Type-2 cycle - lagoon to nearshore

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<td>Soil</td>
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<td>Supratidal sabhka</td>
<td>Evaporitic dolomudstone (MF11)</td>
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<tr>
<td>Inter- to supratidal mudflat</td>
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<td>Intertidal beach</td>
<td>Oolitic grainstone (MF9)</td>
<td>C2</td>
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<tr>
<td>sub- to intertidal lagoon</td>
<td>Laminated mudstone (MF8)</td>
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<td>Argillaceous mudstone (MF7)</td>
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**Note:** Thickness of each environment is indicated.
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<tr>
<th>Lithofacies associations</th>
<th>Microfacies</th>
<th>General descriptions</th>
<th>Depositional environment</th>
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<tr>
<td>LFA-H1</td>
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<td>Dark blue-grey microcrystalline massive argillaceous mudstone; locally dolomitization; detrital grains; stylolites</td>
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<td>LFA-H2</td>
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<td>Light to dark blue-grey, planar to wispy parallel, thin- to non-laminated mudstone; microcrystalline micrite, locally dolomitization; detrital grains; rare replaced gypsum and anhydrite crystals</td>
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<tr>
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<td>Thin planar to wavy parallel bindstone, brownish to bluish-grey, closely-packed tubular filaments and clumps of fragments of micro-organisms; microcrystalline micrite, locally dolomitization; detrital grains; rare replaced gypsum and anhydrite crystals</td>
<td>Sub- to intertidal organic mound and pinnacle</td>
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<tr>
<td>LFA-H4</td>
<td>MF4</td>
<td>Light blue-grey, fine- to medium-grained, moderately-sorted, peloidal wackestone-packstone; microcrystalline micritic matrix, locally dolomitization</td>
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<tr>
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<td>Light blue-grey, stromatolitic boundstones; stromatolitic mats and clumps of fragments of micro-organisms; SH- to LLH-type Conophyton; microcrystalline micritic matrix, locally dolomitization; fenestrae; locally mudcracks</td>
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<td>LFA-C1</td>
<td>MF6</td>
<td>Light blue-grey, medium- to well-sorted, oolitic packstone-grainstone; planar or trough cross laminations; peloids; locally dolomitization; interparticular calcite cements; mudcracks</td>
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<td>MF7</td>
<td>Thin-bedded dark-grey, locally pale pinkish argillaceous mudstone; microcrystalline micrite, locally dolomitization; argillaceous seams and stylolites; abundant replaced gypsum and anhydrite crystals</td>
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<td>MF8</td>
<td>Dark grey planar to wavy parallel, thin laminated mudstone; oblique and cross-laminations; microcrystalline micrite, locally dolomitization; abundant replaced gypsum and anhydrite crystals</td>
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<td>LFA-C2</td>
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<td>Coarse grained, well-sorted, tightly-packed oolitic grainstone; planar or low angle cross lamination; locally dolomitization or silicification; interparticular calcite cements; mudcracks</td>
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<td>MF10</td>
<td>Thin microbially planar and wavy parallel laminated mudstone; microcrystalline micrite, locally dolomitization; fenestrae; abundant replaced gypsum and anhydrite crystals; mudcracks; pedogenic crusts</td>
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<td>LFA-C3</td>
<td>MF11</td>
<td>Evaporitic dolomudstone; equigranular xeno- to hypidiotopic dolomitic matrix; brownish to bluish white replaced gypsum crystals, nodular anhydrite and interbeds of anhydrite, chicken-wire structure; mudcracks; hardgrounds</td>
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<td>LFA-C4</td>
<td>MF12</td>
<td>Dark, rarely yellowish-orange, millimetric-thick crusts of slightly undulated laminations; in-situ brecciation of dolomitized limestone; locally oolites and peloids; abundant replaced gypsum and anhydrite crystals; mudcracks</td>
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