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Stratigraphy, palaeontology and geochemistry of the late Neoproterozoic Aar Member, southwest Namibia: Reflecting environmental controls on Ediacara fossil preservation during the terminal Proterozoic in African Gondwana

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ABSTRACT

Common, Ediacaran fossils are well preserved in a Late Neoproterozoic (ca. 545 Ma) shallow marine sequence, described here as the Aar Member of the Dabis Formation (Kuibis Subgroup, Nama Group), near Aus in southwest Namibia. This 31–38 m thick, shale-dominant unit records the transition from fluvial-shallow marine Kliphoek Sandstone to open marine limestone of the Mooifontein Member of the Zaris Formation, deposited on a subsiding continental margin during a major, regional transgression. Thin sandstone beds contain fossils at a number of levels throughout the Aar Member. Concentrations of *Pteridinium* were mostly transported in flood-derived sheets, while some *Ernietta* assemblages are preserved close to *in situ*. *Rangea* has also been transported, and is mostly confined to thin sandstone lenses incised into mudstone. Limestone beds, common throughout, include at least two marker horizons that can be followed regionally and show local evidence of storm reworking. Systematic sampling and analyses of limestone reveals enrichment in both ^{13}C and ^{18}O higher in the section, with negative $\delta^{13}C$ near the base rising to moderate positive values near the top. The negative-to-positive transition in $\delta^{13}C$ values is more pronounced in the east, with all of the lower Aar Member samples consistently depleted in ^{13}C. While this may reflect greater degrees of alteration by meteoric or dewatering fluids, the same carbonates are notably enriched in ^{18}O relative to those at the same stratigraphic position to the west. The overall rise in ^{13}C is attributed to greater proportional burial of organic matter and release of oxygen to surface environments, while the spatial variability is likely the result of a strong surface-to-deep carbon isotopic gradient in seawater. A number of the fossils, especially *Rangea*, are encrusted with jarosite, an iron-bearing sulphate mineral and common weathering product of pyrite. This observation suggests that preservation of the fossils may have resulted from the rapid encrustation of pyrite on the surface of the organisms as they decomposed and were consumed by sulphate-reducing bacteria within the sandy, near shore sediments. Insofar as pyrite formation requires iron, which is soluble and reactive in anoxic solutions, it is likely that the deeper subtidal environments lacked oxygen. *In situ* pyritized forms like *Ernietta* may have developed the capacity to survive under episodically anoxic or sub-oxic environmental conditions, while *Pteridinium* and *Rangea* lived within an oxygenated estuarine or fluvial setting and were transported during storms to anoxic, ferruginous environments where they were exquisitely preserved.

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1. Introduction

The recent discovery of over one hundred exquisitely preserved specimens of the late Ediacaran Period fossil *Rangea* (Vickers-Rich et al., 2013) on Farm Aar in southwest Namibia prompted new sedimentological and geochemical investigations of uppermost Kuibis Subgroup strata (ca. 550–555 Ma: Grotzinger et al., 1995; 545–548 Ma: Narbonne et al., 2012). The investigated stratigraphic interval preserves carbon and sulphur isotope evidence of significant environmental change, which is considered here in context of the evolution, diversification, and taphonomy of Earth's earliest metazoans. In particular, morphologic details of the newly discovered *Rangea* fossils are preserved in jarosite (an iron-bearing sulfate mineral) coatings, which are likely the oxidative weathering products of early diagenetic pyrite (e.g., Gehling, 1999). Astrobiological interest in jarosite stems from its presence on the surface of Mars, which potentially indicates wet, acid, and sulfate-rich conditions early in planetary history (Squyres et al., 2004). In association with these Ediacara fossils, jarosite may be related to environmental contrasts between deep and shallow marine settings and their unusual mode of preservation.

The oldest examples of the late Neoproterozoic Ediacara biota in the Kuibis Subgroup occur in strata that preserve a globally recognized positive carbonate carbon isotope anomaly (Kaufman et al., 1991; Saylor et al., 1998). Insofar as these events reflect the greater proportional sequestration of organic matter in sediments and release of oxidants (Hayes, 1983), the first appearance of the Ediacara biota in Namibia may be directly associated with the rise of oxygen in shallow marine environments. In this study we analyzed the carbon, oxygen, and sulphur isotope compositions of carbonate and siliciclastic samples from three closely spaced sections through a transitional interval, which is here newly defined as the Aar Member of the Kuibis Subgroup. In order to further understand environmental change coincident with the origination and evolution of the Ediacara biota, time-series trends in carbon isotope abundances were compared against fossil distributions in the Aar Member.

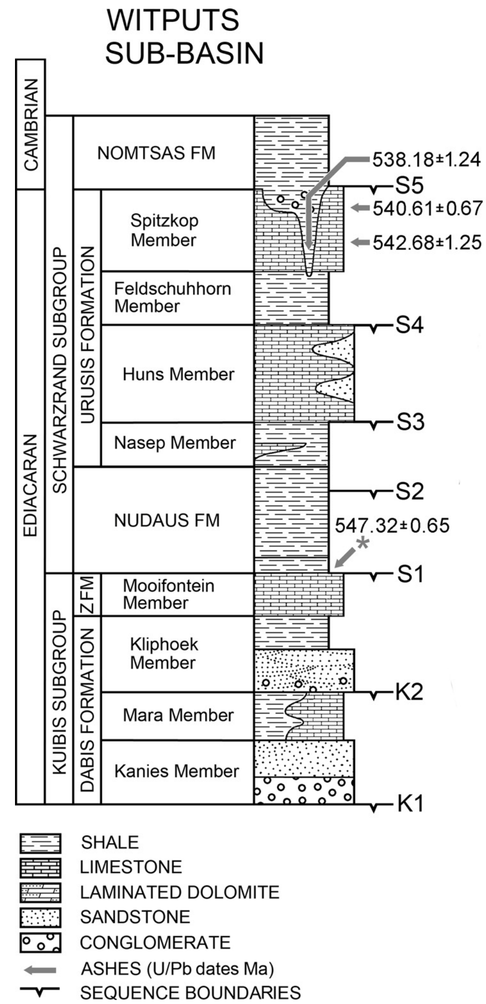

Fig. 1. Regional Stratigraphy of the Nama Group, southern Namibia, showing the positions of the newly named Aar Member and renamed Kliphoek Sandstone, subdivisions of the original Kliphoek Member.

2. Regional geology

Deposition of Ediacaran Period sediments on the Kalahari Craton, including the Witvlei and Nama groups and their lateral equivalents, is described as occurring in a foreland basin that developed during convergence of the Damara and Gariep fold belts (Germs, 1983, 1995; Gresse and Germs, 1993). Saylor (1993), Saylor and Grotzinger (1997), and Saylor et al. (1995, 1998, 2005) provided a detailed sequence stratigraphic framework that placed glacial horizons (Hoffmann, 1989; Kaufman et al., 1991) and a diverse assemblage of terminal Neoproterozoic fossils, including traces of the Ediacara biota and the earliest biomineralizing organisms (Crimes and Germs, 1982; Germs, 1983; Grant, 1990; Grotzinger et al., 1995, 2000) in the context of radiometric age constraints (Grotzinger et al., 1995) and profound carbon and strontium isotope variations (Kaufman et al., 1991, 1993, 1997; Derry et al., 1992; Jacobsen and Kaufman, 1999).

The fossiliferous Nama Group has been further subdivided into the Kuibis and Schwarzrand subgroups (Fig. 1). Typical late Ediacaran Period fossils, including forms such as *Ernietta*, *Pteridinium*, *Swartpuntia*, and *Rangea* (Pflug, 1966, 1970a, 1970b, 1972; Germs, 1972, 1983; Grazhdankin and Seilacher, 2005; Grotzinger et al., 1995; Narbonne et al., 1997; Pflug, 1966, 1970a, 1970b, 1972), vendotaenids (Germs et al., 1986), *Cloudina* (Germs, 1983; Grant, 1990) plus other calcified fossils (Grotzinger et al., 1995, 2000) and carbonized remains (Leonov et al., 2010), have been recovered from sediments both north and south of the palaeostructural high Osis Ridge in the Zaris and Witputs sub-basins, respectively. The stratigraphically youngest Ediacara-type fossils, including *Swartpuntia*, lie 60 m below the Ediacaran–Cambrian boundary in the more southerly portion of the Witputs sub-basin (Narbonne et al., 1997), while the oldest occur in the Mara Member of the Kuibis Subgroup (Saylor et al., 1995).

The Kuibis Subgroup, the focus of this study, is thickest near the Damara and Gariep fold belts and thins until the subgroup completely disappears over the Osis Ridge (Germs, 1983, 1995; Gresse and Germs, 1993). The subgroup has been further subdivided into the sandstone-dominated Dabis and carbonate-dominated Zaris formations, which comprise three unconformity-bounded sequences. Relevant to this study are the K1 and K2 sequences. In the region around Farm Aar, K1 comprises the Kanies Member of the Dabis Formation, which unconformably overlies crystalline basement and includes a basal unit of coarse, tabular-bedded sandstones with small wave-generated ripples and desiccation cracks interpreted as tidal-flat deposits. The upper part of K1 above the Kanies Member is the carbonate-dominated Mara Member, which contains the oldest reported remains of *Cloudina* in the Namibian stratigraphy. Carbonates in the K1 sequence are uniformly depleted in ^{13}C with $\delta^{13}C$ values as low as −6‰ (Kaufman et al., 1991; Saylor et al., 1998; Ries et al., 2009). In contrast, sequence K2 is typified by upward-increasing $\delta^{13}C$ values that define the rising limb of a positive excursion. In the Witputs sub-basin K2 is represented by