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Megaripples from the Mesoproterozoic of the Kimberley region, northwestern Australia and its geological implications

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Abstract Large ripples are described from the Mesoproterozoic Hilfordy Formation in the Kimberley region, northwestern Australia. Both ripple index (*RI*) and ripple symmetry index (*RSI*) suggest the Kimberley ripples were likely generated by storm waves. Their wave height is up to 15−23 cm and wave length is up to 70−90 cm. These features, incorporated with other morphological characteristics such as symmetry, steepness, ripple spacing, and compositions, agree well with the megaripples previously reported from the intertidal-nearshore settings of modern seas and the geological past. The Mesoproterozoic ripples were likely generated by the storm-induced flows. Literature survey of the global record of megaripples reveals that such structures have occurred through the geological past from the Archean to present day. They were particularly common in the Neoproterozoic and had the largest ripple length and ripple height among the modern and geological records. This is probably because extreme storms prevailed at that time. Their frequent occurrence in present day beach is probably due to the prevalence of extreme storms caused by the monsoon or tsunami/earthquake influenced climatic regimes.

Key words megaripples, palaeohydrodynamics, extreme storms, Mesoproterozoic, Hilfordy Formation, Kimberley, northwestern Australia

1 Introduction

Megaripples were originally referred to as bedforms that have a wave length of 100−500 cm and a height of 10−50 cm and are commonly present in the natural surf zone along sandy coasts (Clifton *et al*., 1971). Later, megaripples were broadened to include the wavy structures possessing wavelengths of less than 100 cm but more than 60 cm (Bhattacharyya *et al*., 1980; Eriksson and Fedo, 1994; Mukhopadhyay *et al*., 2006; Chakraborty *et al*., 2009). These large wavy structures are very common not only on present day beaches but also in the geological past (Hyde, 1980; Cotter, 1985; Eriksson and Fedo, 1994; Ainsworth and Crowley, 1994; Allen and Hoffman, 2005; Mukhopadhyay *et al*., 2006; Whitelaw *et al*., 2007; Chakraborty *et al*., 2009). In particular,

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megaripples have been frequently reported from the late Neoproterozoic (Table 1), a period that witnessed climatic extremes such as the Snowball Earth event and super large storms and the rise of the metazoans in late Ediacaran (Allen and Hoffman, 2005). Growing evidence shows that megaripples are a powerful tool in reconstructing palaeohydrodynamic conditions, analyzing palaeoflow directions, and revealing extreme climates (Larcombe, 1992; Larcombe and Ridd, 1995; Larcombe and Jago, 1996; Gallagher *et al*., 1998; Sarkar *et al*., 2002; Allen and Hoffman, 2005).

Table 1 Stratigraphical framework of the Louisa Downs areas, Kimberley region, northwestern Australia

Stratigraphic unit		Age
Quaternary Tertiary		Cenozoic
Louisa Downs Group	Yurabi Formation Egan Formation	Neoproterozoic
Crowhurst Group	Collett Siltstone Liga Shale Hilfordy Formation	Mesoproterozoic
Kimberley Group	Pentecost Sandstone Elgee Siltstone Teronis Member Warton Sandstone	Palaeoproterozoic

Recently, we have discovered megaripples from the Mesoproterozoic Hilfordy Formation in the Kimberley region, northwestern Australia. Their morphological characteristics (*i.e*. symmetry, steepness, ripple spacing, and ripple height) and compositions agree with previously reported examples of megaripples from the intertidal-nearshore settings. Here, we document the Mesoproterozoic examples from the Kimberley region, NW Australia and discuss their geological implications in a broad context. Palaeogeographic reconstruction of the study areas is beyond this report since other sedimentary structures such as gutter and flute casts are absent. Rather, we attempt to conduct a preliminary investigation on their palaeohydrodynamics based on previous studies on their modern and ancient counterparts.

2 Geological setting

The Kimberley region is situated in the northwestern Australia (Fig. 1A). The Proterozoic sedimentary rocks are exposed in the Kimberley region. The distribution of the Proterozoic sedimentary rocks is controlled mainly by the King Leopold and Halls Creek Orogens (Fig. 1B). The megaripples that are the focus of this study are found along the slope of an unnamed hill (S18˚20´32.3˝, E126˚46´07.6˝), about 10 km from the southern margin of the Goat Paddock crater in the Louisa Downs areas of the Kimberley region (Harms *et al*., 1980; Figs. 1C, 2A). In the Louisa Downs areas, the Precambrian successions consist of the Palaeoproterozoic, the Mesoproterozoic and the Neoproterozoic (Table 1). Of these, the Palaeoproterozoic successions were assigned to the Kimberley Group, which comprises four units: the Warton Sandstone, Teronis Member, Elgee Siltstone and Pentecost Sandstone (Roberts *et al.*, 1968; Table 1). The oldest rock of the Pentecost Sandstone is conformably overlain by the Hilfordy Formation of the Crowhurst Group (Roberts *et al.*, 1968; Table 1). The Mesoproterozoic rocks were referred to as the Crowhurst Group, which is composed of the Hilfordy Formation, Liga Shale and Collett Siltstone (Table 1). It underlies conformably the Liga Shale Formation of the same group (Roberts *et al.*, 1968; Tyler *et al*., 1998; Table 1). These Palaeoproterozoic to Mesoproterozoic Formations are occasionally overlain by Neoproterozoic and Cenozoic deposits. The Neoproterozoic Louisa Downs Group consists of five formations, but only the Egan and Yurabi Formations are exposed in Louisa Downs (Roberts *et al.*, 1968).

Megaripples documented here are preserved on the bedding panes of coarse sandstone of the Hilfordy Formation (Fig. 1C). In the study area, the Hilfordy Formation is characterized by thick-bedded (25–70 cm) coarse sandstone (Fig. 2B). Tabular cross-bedding and large-angle cross-bedding are occasionally present (Fig. 2C, 2D). Megaripples occur solely on bedding planes of reddish coarse quartz sandstone (Fig. 3A–3G).

3 Petrographic description

The reddish quartz arenite has a grain-supported texture in thin section, and is composed predominantly of monocrystalline quartz, with minor amounts of feldspar grains. Quartz grains are remarkably uniform in size, well-sorted and relatively rounded (Fig. 2E). Quartz grains range from 2 mm to 4 mm in size, with a mean value of 3 mm; the grain sizes between 2.8 mm to 3.8 mm are the most frequently present (Fig. 4). Thin sections show occasional alignment of opaque minerals, angular quartz and kaolinite. Mica comprises mainly muscovite grains, which are in elongate lath form and commonly present in association with opaque materials. Muscovite laths are often partially altered to kaolinite. Detrital clay minerals are commonly compacted into intergranular pore space.