A squall by the seashore *ca* 2.3 billion years ago: Raindrop imprints in a Paleoproterozoic tidal flat deposit, Kungarra Formation, Western Australia.

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Short running title: Paleoproterozoic raindrop imprints

In this contribution, we describe the occurrence of well-preserved Paleoproterozoic raindrop impact imprints on two surfaces of rippled siltstone–mudstone from the uppermost part of the Paleoproterozoic Kungarra Formation, Turee Creek Group, Western Australia. The raindrop imprints appear on the tops of two immediately overlying bedding surfaces in siltstone, near the top of a shallowing upward sequence that progresses from sandstone to mudstone. Imprints are circular to elliptical with an average diameter of 2–3 mm and a maximum length of 6.3 mm when elliptical. Flat ripple crest morphologies, varied ripple crest orientations, and marks of standing water in the ripple troughs indicate very shallow water conditions. When combined with sedimentological data from the underlying Kungarra Formation (shallow marine sandstones and siltstones), and mature quartz arenites of the overlying Koolbye Formation (mixed tidal, beach, fluvial and eolian), the interval examined is interpreted as a tidal flat deposited during a falling stage systems tract.

INTRODUCTION

Raindrop imprints in sedimentary rocks are a rarity because of their delicate nature and the difficulty of preservation in exposed, but wetted, soft sediments. Precambrian raindrop imprints are even more extraordinary. To our knowledge, the oldest raindrop imprints described are from the Neoarchean Ventersdorp Supergroup (van der Westhuizen *et al.* 1989) and Fortescue Group (Rasmussen *et al.* 2009). However, the interpretation of some of these older imprints is controversial, as hail impact craters and storm downburst impact craters have also been suggested for these structures (Altermann & Lenhardt 2012; Smith 2012; Som *et al.* 2012; Trendall 2012).

The Paleoproterozoic Turee Creek Group of Western Australia is a 4 km thick, conformable sequence of siliciclastic, glaciogenic, and chemical (carbonate) sedimentary rocks deposited during the period of the Paleoproterozoic rise of atmospheric oxygen, in the interval between 2.45–2.22 Ga (Trendall 1979; Martin 1999; Williford *et al.* 2011; Van Kranendonk & Mazumder 2015; Van Kranendonk *et al.* 2015). Preserved at low metamorphic grade, the Turee Creek Group is the only succession in the world that contains a conformable Paleoproterozoic succession both into, and out of, two glacio-eustatic cycles (Van Kranendonk & Mazumder 2015), yet little was previously known in detail about the stratigraphy or tectonic setting of this group, other than a detailed description of glaciogenic rocks of the Meteorite Bore Member in the middle part of the lower Kungarra Formation (Martin 1999) and a general description of the group as a shallowing-upward succession (Martin *et al.* 2000).

Recent detailed mapping of the Turee Creek Group has revealed a significantly more complex and varied depositional environment than previously documented. For example, whereas the Kungarra Formation was interpreted as entirely deep marine (Martin *et al.* 2000), recent results have shown that the upper half of the formation was deposited under relatively shallow marine conditions (above wave base; Van Kranendonk *et al.* 2015; Mazumder *et al.* 2015) and contains two glacio-eustatic cycles of marine regression and transgression (Van Kranendonk & Mazumder 2015).

In this contribution, we add to the increasing understanding of the depositional and stratigraphic setting of the Turee Creek Group by describing a section of rippled tidal flat deposits of siltstone and mudstone in the uppermost part of the Kungarra Formation, at the transition to the overlying Koolbye Formation. The tidal flat deposits contain two superposed horizons with raindrop imprints, indicative of at least temporary emergent, supratidal conditions. The raindrop imprints vary from small, circular pits to larger, elongate impressions oriented perpendicular to ripple crests, indicating precipitation during an onshore squall. The raindrop horizon is placed within sedimentological and stratigraphic contexts, which indicate deposition during a falling stage systems tract from the Kungarra to the Koolbye formations.

REGIONAL STRATIGRAPHY

The Paleoproterozoic Turee Creek Group of Western Australia is exposed along the southern margin of the Pilbara Craton, where it conformably overlies deep, quiet-water shales and banded iron-formations of the 2.63–2.45 Ga Hamersley Group (Trendall 1979; Van Kranendonk *et al.* 2015). The Turee Creek Group is unconformably overlain by sedimentary conglomerate and mature quartz arenites of the 2.22 Ga Beasley River Quartzite (lower Wyloo Group), deposited under fluvial to eolian conditions (Figure 1; Van Kranendonk & Hickman 2012; Mazumder & Van Kranendonk 2013;

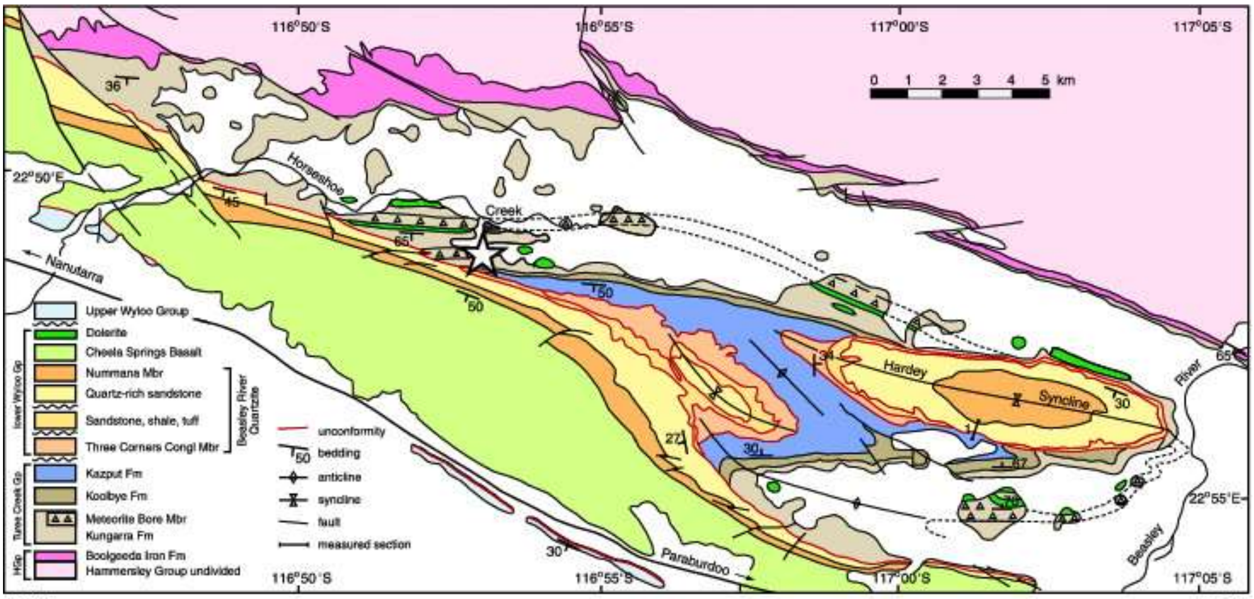

Figure 1 Geological map of the Hardey Syncline in Western Australia, showing the location of the study area (star).

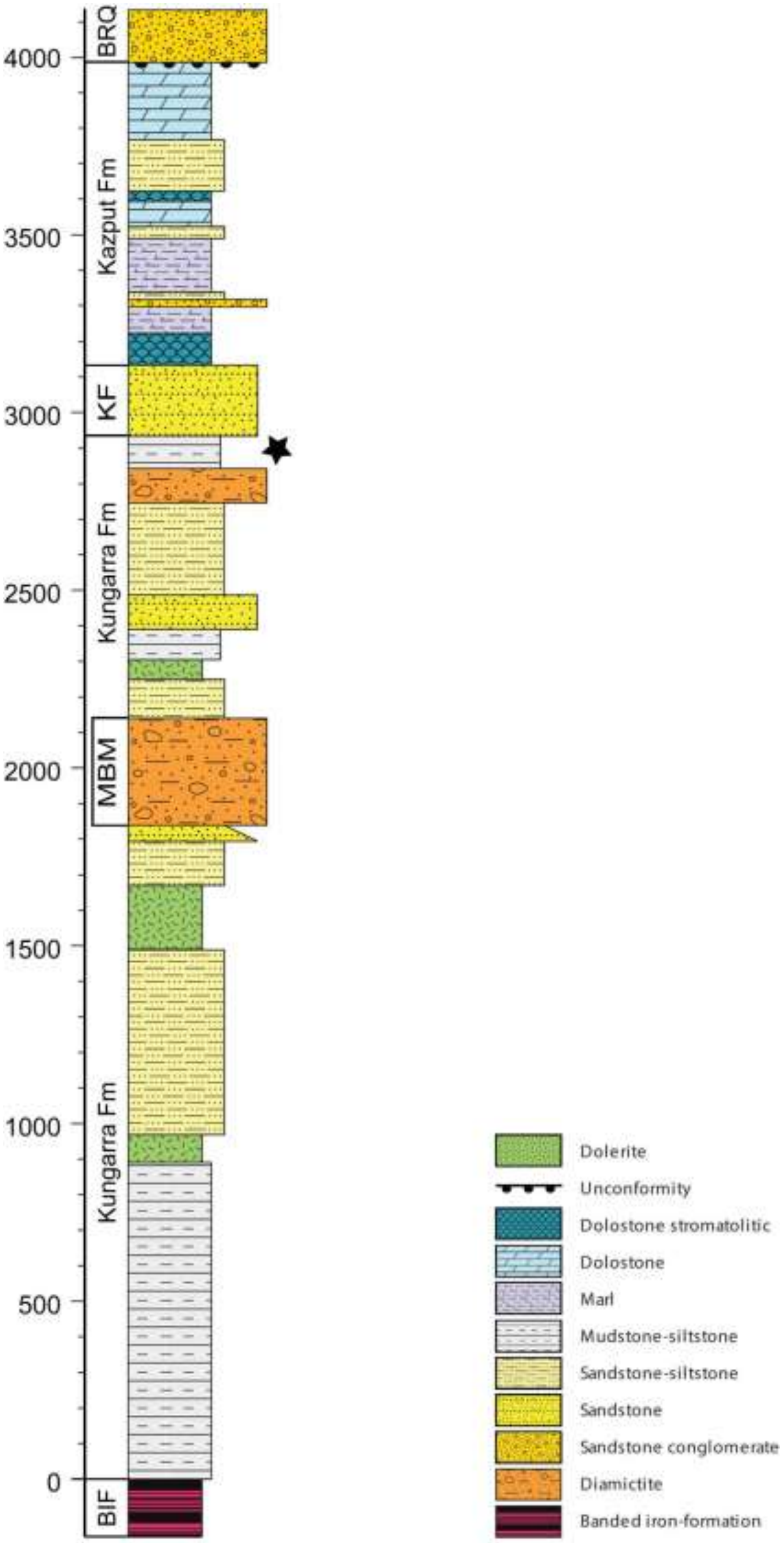

Figure 2 Stratigraphic column of the Turee Creek Group, showing location of the raindrop imprints. BIF = Boolgeeda Iron Formation of the Hamersley Group; BRQ = Beasley River Quartzite, the lower most formation of the Wyloo Group.

Van Kranendonk *et al.* 2015). Although there are no direct age constraints on the Turee Creek Group, it is constrained to between 2.45–2.2 Ga by dates from the underlying and overlying units, and a detailed S-isotope study has confirmed that the group was deposited across the rise of atmospheric oxygen at about 2.4–2.3 Ga (Williford *et al.* 2011; Van Kranendonk *et al.* 2015).

The Turee Creek Group reaches a maximum exposed thickness of ~4 km in the Hardey Syncline, where parts of the succession are locally very well exposed at prehnite–pumpellyite metamorphic grade (Martin *et al.* 2000; Van Kranendonk *et al.* 2015). Thorne & Tyler (1996) divided the Turee Creek Group into three conformable formations, including from base to top: the Kungarra Formation, the Koolbye Formation, and the Kazput Formation (Figure 2).

The ~3 km thick Kungarra Formation lies conformably on the Boolgeeda Iron Formation across a transitional contact zone consisting of shale and up to 7 interbedded units of iron-formation and chert that becomes progressively less iron-rich upsection (Van Kranendonk *et al.* 2015). The middle to upper part of the Kungarra Formation contains two units of glaciogenic diamictite interbedded with commonly rippled, fine-grained sandstones and siltstones that overlie thin carbonate intervals with stromatolites (Van Kranendonk *et al.* 2015).

The 350 m thick Koolbye Formation lies conformably on the Kungarra Formation and consists of mature quartz arenites, with common trough cross-beds and channels, and local cross-beds with heavy mineral bands (Mazumder *et al.* 2015). The Koolbye Formation passes conformably up into the Kazput Formation, which consists of ~650 m of interbedded stromatolitic and thinly bedded, relatively deepwater carbonates, rippled fine-grained sandstones, and organic-rich black shales (Martin *et al.* 2000).

SEDIMENTOLOGY OF THE STUDY AREA

A well-exposed stratigraphic section of the uppermost Kungarra Formation that immediately underlies the mature quartz arenites of the Koolbye Formation was traversed on a steep hillside of the southern side of the valley occupied by Horseshoe Creek (at Zone 50K, E488415, N7472201) (Figures 1, 2). Bedding strike and dip direction are 090°/60°S. At the studied section, the beds consist of mm–cm intercalation of siltstone and mudstone, with abundantly rippled bedding plane surfaces (Figure 3a–c). The total exposed section is 30 m thick and overlies rippled, fine- to medium-grained sandstones (lithic wackes) with local horizons of mud-chip breccia.

In cross-section, ripples vary from symmetrical to asymmetrical (Figure 3c). Bedding surfaces reveal a variety of ripple morphologies, including uncommon straight-crested ripples, and common sinuous-crested and bifurcating ripples (Figure 3a, b). Interference ripples were also observed on a bedding plane that is only 50 cm below sinuous-crested ripples (Figure 3d). One bedding plane was observed to have short (10 cm) crescentic ripples indicative of wind-blown detritus in very shallow water (e.g. mm) conditions. Paleocurrent measurements cluster around southerly directions but wave ripples suggest E–W wave action.

In the section of rippled beds with raindrop imprints, but in areas without pit preservation, elongated marks of standing water in ripple troughs are preserved (Figures 3a, 4). These marks are delineated by long, tiny lines marked by a minute ridge or scarp along, and parallel to the sides of the ripples. Such, often less than a mm high, ridge marks are formed by mm deep water pools that erode silt and mud grains from ripple flanks by slightly oscillating movement of the ponded water, usually caused

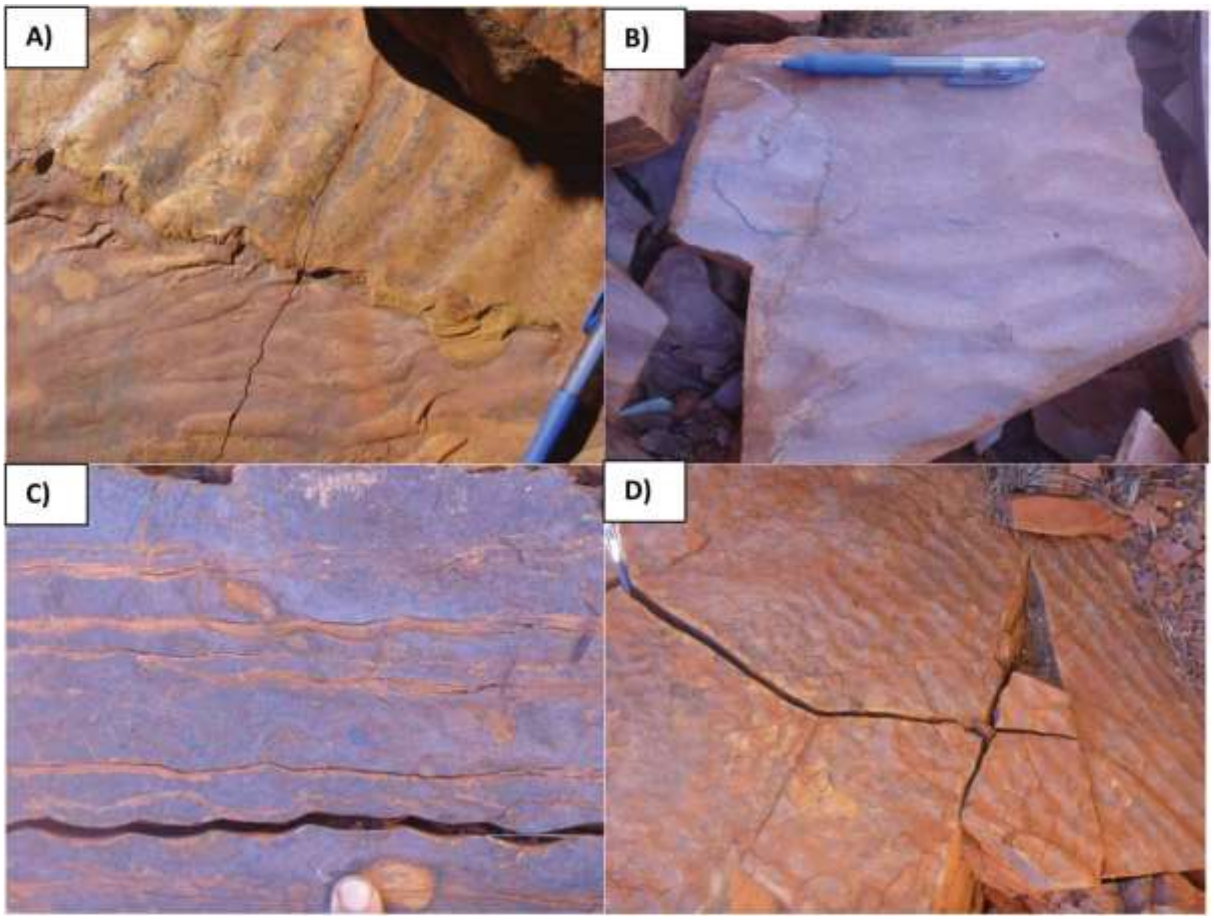

Figure 3 Outcrop photographs of ripples at the top of the Kungarra Formation in the study area: (a) Underside view of two directions of ripples with flat crests in superposed siltstone/mudstone layers; (b) bifurcating ("tuning fork) ripple crests; (c) cross-sectional view of near-symmetric, low amplitude ripples; and (d) underside view of flat-crested, bifurcating ripples.

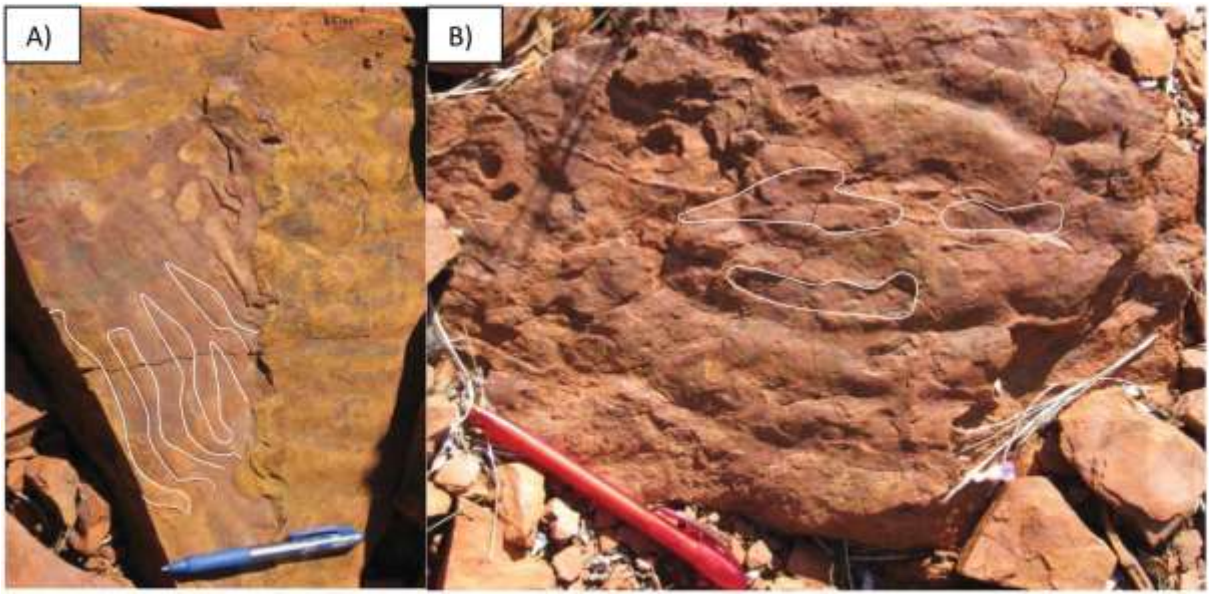

Figure 4 Elongated marks of standing water in ripple troughs from tidal flat siltstones immediately underlying the raindrop imprint horizon: (a) annotated sketch of Figure 3a), showing long, tiny lines marked by a minute ridge or scarp along and parallel to the sides of the ripples, indicative of standing water; and (b) underside view of standing water marks between ripples in siltstone.

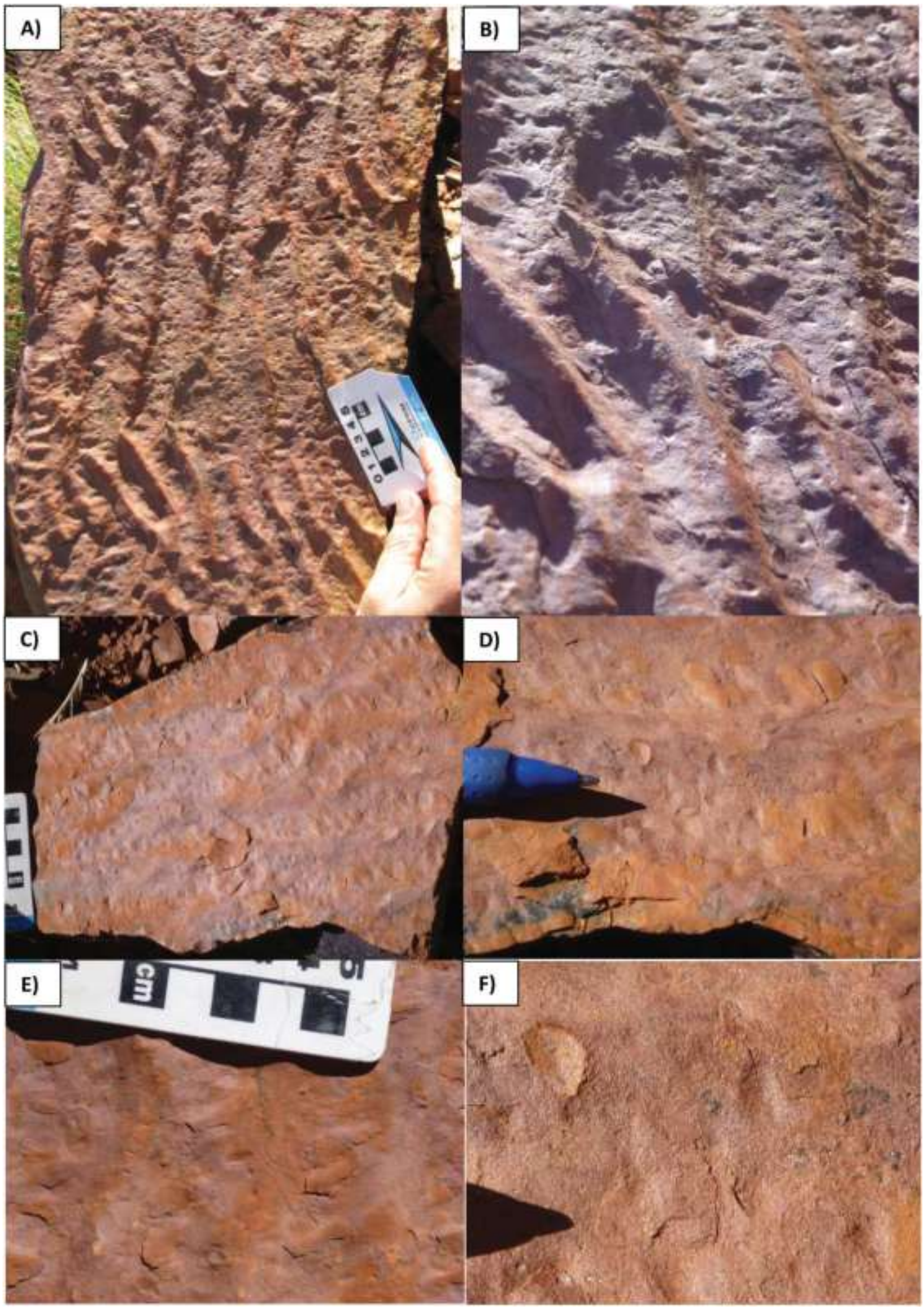

Figure 5 Rippled siltstone with raindrop imprints: (a) outcrop exposure of rippled siltstone with abundant, small circular pits (width of outcrop surface = 30 cm); (b) close-up view of outcrop surface of dominantly circular, small, raindrop imprints (width of view = 5 cm); (c) sample with clearly elongate raindrop imprints oriented at right angles to ripple crests; (d) close-up of (c), showing elongated raindrop imprints, some of which have deeper pits on ripple flanks towards top of mage; (e) close-up view of elongated raindrop imprints, near perpendicular to ripple crests; and (f) detailed view of elliptical raindrop imprints in siltstone.

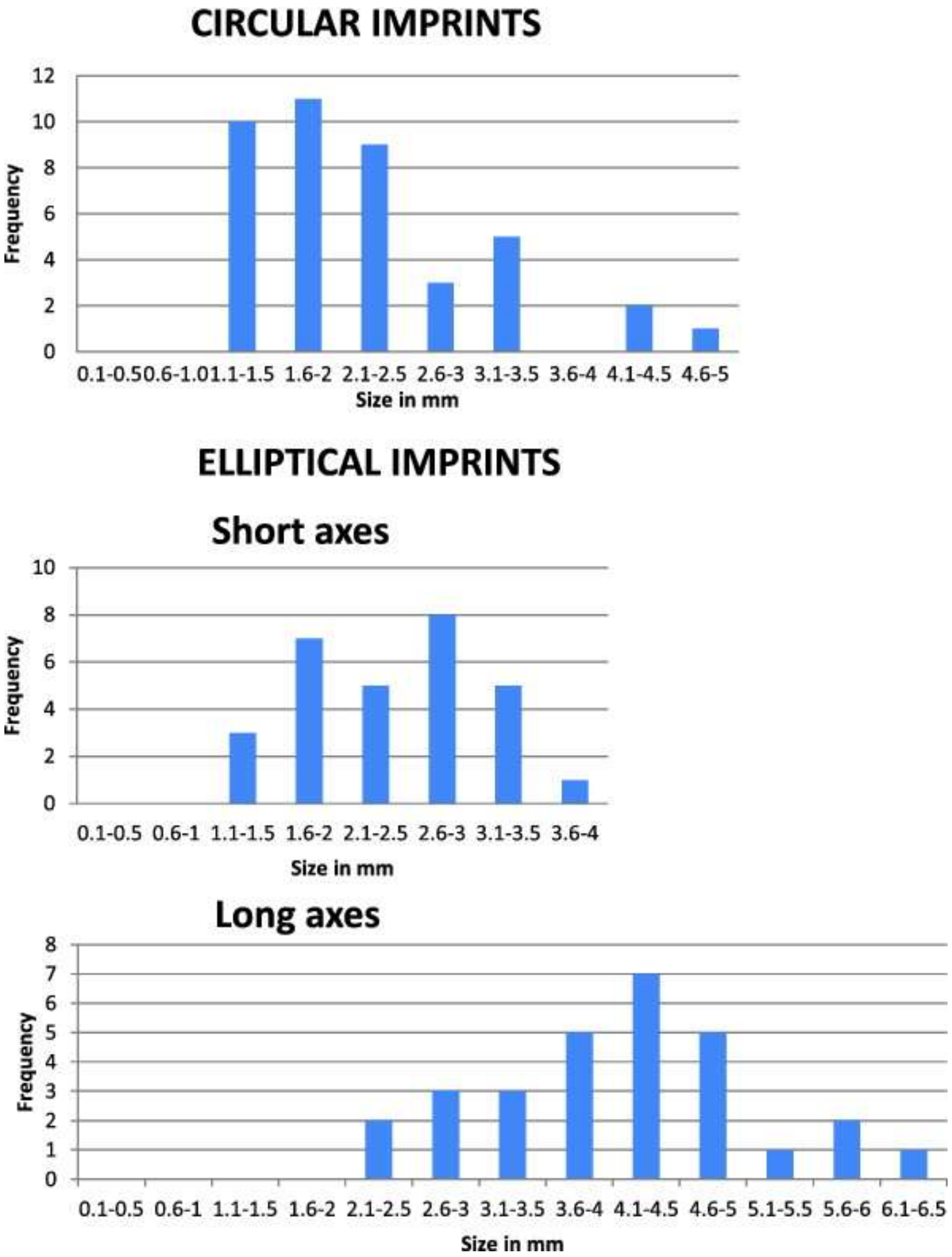

Figure 6 Histograms of measured raindrop imprints. Top = circular imprints; Bottom = short and long axes of elliptical imprints.

by wind. The grains are deposited in the ripple troughs smoothing out the trough depth. Similar marks were described from the Neoarchean of South Africa by Altermann & Lenhardt (2012) from formations also bearing raindrop imprints. The preservation of such marks is extremely rare but can be expected on rippled bedding surfaces, when the rainwater cannot run off completely and forms pools between ripple crests.

RAINDROP IMPRINTS

Midway up the exposed section of the Kungarra Formation studied here are two directly superimposed, thin (mm-scale) horizons of rippled siltstone with evenly, but randomly, spaced circular to elliptical depressions (pits) across both ripple crests and in ripple troughs (Figure 5a–d). The two raindrop imprint horizons lie directly on each other within a series of thinly bedded siltstone–mudstone with pervasive low-amplitude current ripples, including uncommon straight-crested ripples and more common sinuous-crested, bifurcating and interfering ripples (Figure 3d).

The ripple crest directions of the two horizons with raindrop imprints vary by ~ 40 to 45 degrees from each other. Whereas the upper horizon displays symmetrical to slightly asymmetrical, bifurcating ripples of 2–3 cm wavelength, ripple crests in the lower horizon are prevalently straight and asymmetrical, with a wide stoss (luv) side and shorter and steeper lee sides, with ripple wavelength of 3–4 cm on average.

The raindrop imprint pits range from 1.0–6.3 mm in diameter but are in majority 2–3 mm in width and up to 6.3 mm in length, when elliptical (Figure 6; Table 1). The upper horizon with the smaller ripples is occupied by less frequent and generally smaller imprints, while the lower horizon displays more frequent, more often overlapping, and larger pits, indicative of heavier rain fall.

The density of the imprints on the bed surfaces varies, with pits spaced generally about 0.5 to 1 cm apart but with rare imprints overlapping one another and others that are spaced 3 cm apart. Pits are between 0.5 to 2 mm deep, with gently to moderately sloping margins and smooth concave basal depressions. Elliptical pits have generally more shallow dipping margins along the long axis of the ellipse, and more steeply dipping margins on the shorter sides of the ellipse. Some elliptical pits, however, have a very shallow-dipping margin on one side of the pit long axis and a steep margin on the other side (Figure 5e, f). The density distribution of the imprints is moderate and not many of them show overlap patterns, thus suggesting that the rain precipitation was moderate. However, the elliptical form of many imprints suggests that the rain drops were accelerated by winds and hit the surface at an oblique angle. Steeper-sided imprints are most commonly observed on the stoss side of ripples suggesting formation during an onshore wind, blowing onto the coastline. The wider luv sides of the ripples were oriented perpendicularly to the wind direction. In the ripple troughs and on the wind protected steeper and narrower lee sides, the imprints are less pronounced. This is supported by the smooth and shallow impact craters of the raindrops, independently of their diameter. As the elliptical imprints show heavier imprint on luv side of ripples, it could be argued that the prevailing winds were directed towards the coast, parallel to the coast directed currents.

DISCUSSION

Sedimentary facies analysis and new mapping reveals a relatively deeper water shelf setting (below the storm wave base) during deposition of the bulk of the lower Kungarra Formation, as is evident from monotonous very thick shale with occasional massive to plane laminated (with rare asymmetric ripples) graded fine-grained sandstones (turbidites; Martin 1999; Martin *et al.* 2000; Van Kranendonk & Mazumder 2015; Van Kranendonk *et al.* 2015). However, the depositional setting in the Kungarra Formation became progressively shallower, as evident from the dominance of wave and combined flow ripples with occasional hummocky cross-stratification and longshore bar deposits up-section (Van Kranendonk *et al.* 2015). The occurrence of fine-grained sandstone with desiccation cracks below the raindrop-bearing siltstones confirms intermittent exposure of the depositional surface to

Table 1 Measurements of raindrop imprints and data histograms

Circular imprints

Length from photograph (mm)	4.7	4.4	4.1	3.4	3.3	3.2	3.0	3.0	2.8	2.6	2.5	2.4	2.4	2.3	2.2	2.2	2.1	2.1	2.1	2.1	2.0	2.0	2.0	2.0	2.0	2.0	1.9	1.8	1.8	1.8
Actual length (×1.04166)	4.9	4.6	4.3	3.5	3.4	3.3	3.1	3.1	2.9	2.7	2.6	2.5	2.5	2.4	2.3	2.3	2.2	2.2	2.2	2.2	2.1	2.1	2.1	2.1	2.1	2.1	2.0	1.9	1.9	1.9
Length from photograph (mm)	1.6	1.5	1.5	1.5	1.5	1.5	1.3	1.2	1.2	1.1	1.1																			
Actual length (×1.04166)	1.7	1.6	1.6	1.6	1.6	1.6	1.4	1.2	1.2	1.1	1.1																			

Elliptical imprints

SHORT AXIS																													
Length from photograph (mm)	1.2	1.3	1.4	1.7	1.7	1.8	1.8	1.9	1.9	1.9	2.1	2.1	2.2	2.2	2.4	2.5	2.6	2.7	2.7	2.8	2.8	2.8	2.9	3.0	3.0	3.1	3.3	3.4	3.8
Actual length (×1.04166)	1.2	1.4	1.5	1.8	1.8	1.9	1.9	2.0	2.0	2.0	2.2	2.2	2.3	2.3	2.5	2.6	2.7	2.8	2.8	2.9	2.9	2.9	3.0	3.1	3.1	3.2	3.4	3.5	4.0
LONG AXIS																													
Length from photograph (mm)	2.6	2.1	6.0	2.2	3.1	3.1	4.4	4.4	4.0	4.5	2.7	5.0	3.8	2.9	3.4	3.6	5.6	4.4	3.8	4.4	3.8	4.5	4.0	3.9	4.5	4.3	4.7	4.7	5.5
Actual length (×1.04166)	2.7	2.2	6.2	2.3	3.2	3.2	4.6	4.6	4.2	4.7	2.8	5.2	4.0	3.0	3.5	3.7	5.8	4.6	4.0	4.6	4.0	4.7	4.2	4.1	4.7	4.5	4.9	4.9	5.7

Histogram, circular imprints

Diameter (mm)	0–0.5	0.6–1.0	1.1–1.5	1.6–2.0	2.1–2.5	2.6–3.0	3.1–3.5	3.6–4.0	4.1–4.5	4.6–5.0
Frequency	0	0	10	11	9	3	5	0	2	1

Histogram, elliptical imprints

Diameter (mm)	0–0.5	0.6–1.0	1.1–1.5	1.6–2.0	2.1–2.5	2.6–3.0	3.1–3.5	3.6–4.0	4.1–4.5	4.6–5.0	5.1–5.5	5.6–6.0	6.1–6.5
Frequency (short axis)	0	0	3	7	5	8	5	1					
Frequency (long axis)	0	0	0	0	2	3	3	5	7	5	1	2	1

Measurements were made on a picture copy (0.96 × magnification) of the sample surface, to allow for detailed measurement without damaging the sample.

the atmosphere, indicating an intertidal depositional setting (Reineck & Singh 1980; Johnson & Baldwin 1996; Eriksson *et al.* 1998; Mazumder 2005; Eriksson & Simpson 2012).

Near-symmetric ripples with commonly bifurcating crestlines and the silt/mud composition of the rocks, combined with the presence of ladderback ripples, suggests that the raindrop-bearing siltstones of the uppermost Kungarra Formation were deposited in a tidal flat environment with episodic emergence (De Raaf *et al.* 1977; Reineck & Singh 1980; Collinson & Thompson 1989; Tirsgaard 1993; Baas 1994; Johnson & Baldwin 1996; Mazumder 2005; Eriksson & Simpson 2012; Van Kranendonk *et al.* 2015). Crescentic ripples and raindrops indicate very shallow water to periodically exposed conditions (Reineck & Singh 1980; Allen 1984; Collinson & Thompson 1989). The rapid changes in ripple crest directions between directly overlying sediment beds, the small size of the ripples, the abundance of mud chips in some beds, and the periodic exposure with standing water ponds between ripple crests, and the raindrop imprints are typical signatures of deposition in extremely shallow water. All these features strongly indicate a low energy tidal flat, with shoals and reworking of mud drapes (Parizot *et al.* 2005). Such deposits are usually shoreface sediments at the upper intertidal to supratidal level, above the mean tide (mwl) (Eriksson 1979; Bose & Chakraborty 1994; Johnson & Baldwin 1996; Eriksson *et al.* 1998; Simpson *et al.* 2002; Eriksson & Simpson 2012; Longithano *et al.* 2012). Such fine-grained, rippled mud/siltstones could also be lacustrine; however, lacustrine shoreline deposits are usually very narrow and have a very low preservation potential.

The conformably overlying Koolbye Formation bears excellent herringbone cross-beds, nearly straight crested ripples with tuning fork-like bifurcations, reactivation surfaces, interference ripples and laterally accreted tidal rhythmites, indicating intertidal sedimentation (Mazumder & Arima 2005, 2013; Mazumder *et al.* 2015). This intertidal sandstone conformably grades upward into heavy mineral bearing beach deposits with evidence of eolian reworking (low amplitude ripples and pinstripe lamination) and coastal dunes (Mazumder *et al.* 2015). The coastal sedimentary deposits are overlain by fining-upward sandstone bodies with spectacular channel deposits, indicating deposition as fluvial channels (Mazumder *et al.* 2015).

Thus, the development of the Kungarra to Koolbye succession argues strongly in favour of the fine-grained siltstones with raindrop imprints described here as having been deposited in a tidal flat setting and not as a lacustrine deposit (Martin 1999; Martin *et al.* 2000; Van Kranendonk & Mazumder 2015; Van Kranendonk *et al.* 2015).

The average size of circular raindrop imprints and of the short axes of elliptical raindrop imprints preserved in the uppermost Kungarra Formation are 2–3 mm in diameter and thus fall well within the range of modern, average rainfall (Marshall & Palmer 1948; Best 1950; Willis & Tattelman 1989), but significantly below the largest of the Neoarchean imprints studied by Som *et al.* (2012). Raindrop size is known to vary with the intensity of rainfall, with a smaller average drop size forming under low intensity fall conditions (Marshall & Palmer 1948; Best 1950). Given the scattered nature of the Kungarra imprints, they must represent the results of a low intensity fall (brief, scattered rain), but the elliptical nature of many of the imprints suggests rainfall driven by strong winds, and thus a squall. The mean size of Kungarra imprints suggests raindrop sizes similar to, or slightly larger than, that for average modern rainfall under low intensity conditions (Marshall & Palmer 1948). More data is required before an attempt can be made to estimate the air density at this time.

CONCLUSIONS

A short section near the top of the Paleoproterozoic Kungarra Formation of the Turee Creek Group exposes a succession of rippled siltstone–mudstone units deposited in a tidal flat environment at the transition from deeper water marine conditions to shoreline, fluvial and eolian deposits of the overlying Koolbye Formation. Circular to elliptical raindrop imprints were discovered on two, thin beds of rippled siltstone–mudstone. The imprints are generally widely spaced and range in size from 1–7 mm, averaging 2–3 mm. Pits have deeper margins on the luv side of ripples, indicating a light rain driven by onshore winds, during a squall.

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