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Reply to the Discussion by Callow *et al.* on "Were the Ediacaran siliciclastics of South Australia coastal or deep marine?" by Gregory J. Retallack, Sedimentology, 59, 1208–1236

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Callow *et al.* (2012) conclude with two contradictory statements: (i) "It seems entirely probable, while as yet unproven, that soils or soil-like processes could be present in intertidal to supratidal portions of the Ediacara Member"; and (ii) "On the basis of sedimentological observations, deposition of the fossil-bearing strata within fully marine, tempestite sandstones is considered to be the most parsimonious interpretation". My paper (Retallack, 2012a) presents evidence from a variety of geochemical, petrographic, granulometric and palaeopedological analyses, as well as sedimentological observations, that would appear to falsify their second statement, while supporting their first statement. 'As yet unproven' can be taken as an opinion of a working hypothesis, following Popper's (1968) view that mathematics may offer formal proof, but science can only falsify.

Thus, Callow *et al.* (2012) agree that there are non-marine as well as marine parts of the Ediacara Member, as also argued by Mawson & Segnit (1949), Goldring & Curnow (1967) and Jenkins *et al.* (1983), but not the entirely deep marine interpretation of Mount (1989), and Gehling (2000, and for Fedonkin *et al.*, 2008). Callow *et al.* (2012) are mistaken in asserting that marine facies and hummocky cross-stratification were not mentioned or illustrated by Retallack (2012a). Hummocky cross-stratification illustrated by Gehling (2000) and heterolithic intertidal facies illustrated by Jenkins *et al.* (1983) were both mentioned and incorporated in an explicit reinterpretation of sequence stratigraphy of the Ediacara Member, that included horizons of marine influence (Retallack, 2012a, p. 1214, figs 4D and 6). In their original description of hummocky cross-stratification, Dott & Bourgeois (1982) used examples from deltaic sandstones of the Eocene Coaledo Formation of Oregon, familiar to this author from many years of student excursions. Subsequent discoveries of hummocky stratification have been in shoreface to shallow marine shelf palaeoenvironments, not the deep ocean (Higgs, 2011).

Callow *et al.* (2012) also note: "Here it is concluded that analysis of demonstrably subaqueous, and most probably marine, microbial mat fabrics has led Retallack (2012a) towards mistaken conclusions about his subaerial palaeosols". This does not follow as a conclusion, because demonstration that mat fabrics of the Ediacara Member are subaqueous cannot be found in their preceding discussion. The South Australian Ediacaran mat fabrics are detailed by Retallack (2012a), as well as another recent publication (Retallack, 2012b), which develops general criteria for discrimination of microbial mats (marine-lacustrine) and microbial earths (non-marine subaerial). In summary, microbial earths have vertically oriented organisms intimately admixed with minerals of the soil, whereas microbial mats are laminated, and detachable from their mineral substrate as flakes, skeins and rollups. Microbial earths have irregular relief, healed desiccation cracks and pressure ridges even in clay-poor sandstones, whereas microbial mats have flexuous, striated domes and tufts. Microbial earths form deep soil profiles with downward variation in oxidation, clay abundance and replacive nodular subsurface horizons, whereas microbial mats form caps to unweathered, chemically reduced sedimentary layers. Microbial earths develop increasingly differentiated soil profiles through time, whereas microbial mats build upward in laminar to domed increments. On the basis of these criteria, the healed cracks and ridges characteristic of the microbially induced sedimentary structure designated 'old elephant skin' and its underlying stratal homogenization, nodularization and geochemical differentiation in the Ediacara Member are interpreted as subaerial microbial earths, and not subaqueous microbial mats (Retallack, 2012a).

Three additional issues are highlighted by separate headings of Callow *et al.* (2012), starting with the ambiguity of 'deep marine', which is especially difficult to assess in Ediacaran rocks whose fossils are famously problematic (Antcliffe & Brasier, 2008; Antcliffe *et al.*, 2011). This problem can be simplified into two alternative palaeoenvironments of the Ediacara Member: (i) coastal plain (Jenkins *et al.*, 1983); and (ii) submarine canyon and fan (Gehling for Fedonkin *et al.*, 2008). Turbidites would be expected in the Gehling model, but not in the Jenkins model, and that is why turbidites were emphasized by Retallack (2012a). Callow *et al.* (2012) are correct that many lines of evidence are not diagnostic of either case, and also enumerate much evidence against deep marine conditions published by Gehling (2000), who ironically was one of the co-authors of Jenkins *et al.* (1983). Also debatable is the following statement by Callow *et al.* (2012): "The direct linkage between red colour of a sandstone and depositional setting is of little practical value, particularly in the Proterozoic". Their suggestion that red colour comes from oxidation of pyrite in outcrop is negated for the Ediacara Member by observations of red claystone clasts redeposited from the palaeosols found along with grey sedimentary intraclasts within grey sandstone palaeochannels (Retallack, 2012a). Furthermore, red colour alternates with grey from bed to bed, and is found in deep boreholes under many metres of overlying grey sedimentary rock, as also noted by Mawson & Segnit (1949). The covariation of ferrous–ferric iron ratios with other indices of hydrolytic weathering in palaeosols of the Ediacara Member is evidence that these soils were well-drained and oxidized during the Ediacaran (Retallack, 2012a). No evidence has yet emerged that Ediacaran palaeosols were different from Phanerozoic palaeosols in having this particular redox boundary at the former water table, from ongoing studies in Australia (Retallack, 2012a), Newfoundland (Retallack, 2010, 2012c,d) and Massachusetts (Retallack, 2011). During my own recent visit to the Carding Mill Valley near Longmynd (Shropshire), numerous red palaeosols were observed and sampled in those Ediacaran units designated coastal to alluvial by Salter (1857), McIlroy *et al.* (2005) and Callow & Brasier (2009), but no palaeosols were seen within grey facies which these authors considered fluvial palaeochannels or marine siltstones and shales.

Finally, Callow *et al.* (2012) dispute putative palaeosols of the Ediacara Member, suggesting at first that they may have been unusually complex or atypical red turbidites, but later concluding that they were tempestites. Their suggestion that geochemical strain and mass-balance analysis should be conducted on genuine turbidites or tempestites for comparison with palaeosols is an excellent one, which has recently been applied to tempestites and turbidites in Ediacaran rocks of Newfoundland (Retallack, 2012c,d). Geochemical strain and mass-transfer analysis distinguishes unweathered tempestites and turbidites (which plot in the physical dilation and cation-gain quadrant) from palaeosols (which plot in the physical collapse and cation-loss quadrant: Retallack, 2012a, fig. 12). Stable elements used as proxies for strain (such as Ti and Zr) are mainly in heavy minerals concentrated at the bottom of event beds, whereas in palaeosols such stable elements are enriched at the top of the bed by weathering depletion of unstable minerals and elements. Weatherable cations (Ca^{2+}, Mg^{2+}, Na^{+} and K^{+}) in event beds are concentrated in clayey upper portions, whereas clays in surface horizons of palaeosols are depleted of these cations by chemical weathering. The concept of tempestites works especially well with a fluvial or aeolian model, because in most palaeosol sequences (Retallack, 1986, 1998), deposits of large floods or wind storms separate one palaeosol from the one below, as appears to have been the case in the Ediacara Member (Retallack, 2012a). In contrast, aggrading tidal flats or sea floors show long-term upbuilding of microbial mat fabrics, with little evidence of lengthy pauses in aggradation (Noffke, 2010).

Callow *et al.* (2012) capture well the motivation for my study by stating: "Our expectation is that pedogenic, biological and chemical processes will prove to be markedly different in Ediacaran soils from those found in later Phanerozoic soils". With this acknowledged aim, Retallack (2012a) offers specific models for Ediacaran palaeosols formed on flood and wind tempestites, and a challenge for further testing of a variety of soil-diagnostic features in the Ediacara Member, including mass-balance negative strain and cation depletion, loessic grain-size distribution and texture, unusually light carbon and oxygen isotopic compositions which show linear covariance, and sand crystals of gypsum and micritic replacive nodules with a repetitive depth from the tops of beds. Many more Ediacaran palaeosols and more sophisticated ways of examining them will be needed to fully understand palaeoclimate and palaeobiology at the threshold of animal evolution. This is not the end, but the beginning of a new direction for research on Ediacaran terrestrial palaeoenvironments.

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