WAVES AND WEATHERING ON THE EARLY EARTH: GEOLOGICAL EVIDENCE FOR AN EQUABLE TERRESRIAL CLIMATE AT 3.7 GA. A. P. Nutman[1], V. C. Bennett[2], C. R. L. Friend[3], and M. D. Norman[2] [1]School of Earth and Environmental Sciences, University of Wollongong, Wollongong NSW 2522, Australia (anutman@uow.edu.au), [2]Research School of Earth Sciences, Australian National University, Canberra ACT 0200 Australia, [3]45 Stanway Road, Headington, Oxford OX3 8HU, UK.

Introduction: The presence of banded iron formations (BIF) in the 3.7-3.8 Isua supracrustal belt (Greenland) [1] shows that the surface of the Earth was cool enough by then to sustain liquid oceans. The recognition of relict pillow structures in Isua metabasalts [2, 3, 4, 5] is additional direct evidence of liquid oceans on the early Earth. The question is, 'How cool was cool?' particularly given that at 3.8–3.7 Ga it is thought that the early Sun was delivering 25-30% less thermal energy to Earth than now, as inferred from stellar evolution trends [6]. Was the climate of the early Earth relatively benign, with variable partial to no ice cover, as on the Phanerozoic Earth, or did a global pack ice separate the oceans from a frigid atmosphere? The mere presence of water-lain chemical sedimentary and volcanic rocks near the start of Earth's rock record does not answer this question because they can form under an ocean open to the atmosphere or under an ocean locked under ice.

Here we discuss two lines of geological evidence from Isua metasedimentary rocks which support the idea that Earth's climate at 3.8–3.7 Ga was equable rather than entirely frigid. In addition to providing direct information about the nature of early Earth environments, this study facilitates a comparson between the early surface environments on Earth and Mars in order to understand more generally the environmental conditions of early terrestrial planets, including the evolution of their hydrospheres and atmospheres, and the processes and effects of chemical weathering.

Geological evidence for an equable climate on the early Earth: The first line of evidence is the presence of storm wave structures in chemical sedimentary rocks, which show that the oceans of the early Earth were at least partially ice-free at 3.7-3.8 Ga, so that atmospheric storms could generate waves in the oceans. The second is that some detritus in felsic and politic sedimentary rocks was derived from strongly weathered juvenile arc-crust source regions. Rapid chemical reactions between exposed rocks, the atmosphere and precipitation are most likely with an equable climate sustaining surface liquid water rather than a cold climate with a frozen surface. Finally, given the 25-30% lower solar luminosity at 3.8–3.7 Ga compared with the present [6], topical alternative mechanisms that could have sustained the equable climate are considered.

Storm wave structures in chemical sediments: Chemical sedimentary rocks such as banded iron formation (BIF) and pillow basalts are persistent features of the oldest volcanic and sedimentary record by 3.8–3.7 Ga, and are direct evidence for oceans by the start of the Archean. However, their presence does not dictate an equitable 3.8–3.7 Ga terrestrial climate because they could have formed in oceans below global pack ice on a frigid Earth. The oldest known depositional structures occur as locally preserved features in ca 3.7 Ga deformed, amphibolite facies rocks of the Isua supracrustal belt (Greenland). These include units up to 1 m thick, in which there are stacked or jumbled clasts of chert. Detailed structural analysis shows that these rocks are not tectonic breccias. Also, their reported location in chemical sedimentary units capping slightly older volcanic rocks shows they are unlikely to be mass-flow deposits in a deep basin. In both composition and structure, these units resemble edgewise breccias observed on later Precambrian and Phanerozoic chemical sediment platforms, which formed when laminated sediments are disrupted by storm waves. Hence, the wave origin shows oceans were not ice covered, because in that case atmospheric storms would not generate waves.

Composition of the early atmosphere: The level of carbon dioxide in the atmosphere of the early Earth has been much debated, most recently by [7, 8, 9, 10]. There is growing geochemical and geological evidence from Isua supracrustal belt sedimentary rocks that in the Eoarchean, carbonate formed either directly during sedimentation or during diagenesis [11, 12, 13] However, mass-independent isotopic fractionation (MIF) is strongly dependent on atmospheric pCO_2, because higher concentrations cause increased scattering and UV absorption, which decreases SO_2 photolysis rates [14], thereby dampening the magnitude of MIF. Modelling of Halevy et al. [14] then shows that MIF values of +2 to +3 per mil $\Delta^{33}S$ as recorded for Isua rocks [15, 16] must be supported by higher atmospheric SO_2:H_2S. This could be achieved by higher levels of volcanic activity [14].

Chemical weathering: The Isua supracrustal belt also contains 3.72–3.70 Ga felsic and pelitic sedimentary rocks, derived from juvenile volcanic arc sources. These sedimentary rocks have chemical weathering indices [17] that deviate from those of both fresh Eoarchean and modern igneous rocks. Furthermore, their weathering indices are congruent with rare examples of weathered (not hydrothermally altered) Isua volcanic rocks we have identified. Although higher atmospheric CO_2 and lower fO_2 in near-surface enviroments would strongly influence the chemistry of Eoarchean weathering, this nonetheless shows that these sedimentary rocks contain large contributions from highly weathered source materials. Rapid advanced weathering (these rocks consist of materials shed from an arc) is most feasible with an equable to hot climate, rather than a frigid one, because higher temperatures enhance chemical reactions between rocks, atmospheric gases and precipitation.

Conclusions: Evidence from 3.7 Ga Isua metachemical sedimentary rocks demonstrates wave action in shallow marine settings. In addition, application of the Ohta & Arai weathering index [17] to Isua metadetrital sedimentary rock chemical analyses demonstrates variable to intense weathering of juvenile volcanic arc terranes. Wave-generated structures in chemical sedimentary rocks and advanced weathering at ca 3.7 Ga provide new support for liquid water at Earth's surface and point to an equitable terrestrial climate, with at least partially ice-free oceans [18]. Given that solar heating was 30–25% less at 3.7 Ga than at the present, heat-retention mechanisms are needed to explain this early equable climate. Yet to be resolved is whether this was due to higher atmospheric greenhouse gas abundance (e.g. CO_2, CH_4) or a lower terrestrial albedo owing to an absence of bright landmasses and ice caps.

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