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The Eoarchean legacy of Isua (Greenland) worth preserving for future generations

Allen Phillip Nutman

University of Wollongong, anutman@uow.edu.au

Vickie C. Bennett

Australian National University (ANU), vickie.bennett@anu.edu.au

Clark R. L Friend

Gendale, UK, Chinese Academy of Geological Sciences, crlfriend@yahoo.co.uk

Martin J. Van Kranendonk

University of New South Wales, m.vankranendonk@unsw.edu.au

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**The Eoarchean legacy of Isua (Greenland) worth preserving for
future generations**

Allen P. Nutman^{1,3}, Vickie C. Bennett^{2,3}, Clark R. L. Friend⁴, Martin Van
Kranendonk^{3,5}

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¹ GeoQuEST Research Centre, School of Earth, Atmospheric and Life Sciences,
University of Wollongong, Wollongong, NSW 2522, Australia

² Research School of Earth Sciences, Australian National University, Canberra, ACT
2601, Australia,

³ Australian Centre for Astrobiology, University of New South Wales, Kensington,
NSW 2052 Australia

⁴ Glendale, Tiddington, Oxon, OX9 2LQ, UK

⁵ School of Biological, Earth and Environmental Sciences, University of New South
Wales Australia, Kensington, NSW 2052, Australia

Correspondence should be directed to: Allen Nutman anutman@uow.edu.au

Abstract:

The Eoarchean (>3600 Ma, or millions of years ago) folded and metamorphosed Isua supracrustal belt and the adjacent orthogneiss exposures of Greenland contain rare low deformation lenses that display some uniquely-preserved components of Earth's oldest rock record. These include world's oldest (but contested) stromatolites in dolomitic carbonates, conglomerates, pillow basalts demonstrating submarine eruption, slivers of upper mantle rocks, formation of earliest continental crust by multistage tonalite + diorite emplacement followed by intracrustal granite production. All these diverse occurrences are keys to establish early Earth's processes at the start of the geological record. Although some of these features are preserved at several localities, other critical ones are exposed on only a few m² of rock at single localities or are of historical significance. None of these sites are currently protected, and there is a reliance on responsible sampling to keep them intact for future generations. Given the high interest in the Archean Eon, combined with the increased ease of fieldwork in remote localities, many significant 'Deep Time' localities in not only Greenland but worldwide are in danger of eradication. Here, five key Isua area geological sites are presented, with an explanation of their significance and worthiness for initially reliance on already-collected samples, but hopefully ultimately government protection. This highlights an increasing problem of destruction of *in situ* evidence of Earth's unique early geological heritage and the need for collaboration in protecting and archiving of these key scientific resources.

Keywords: Eoarchean; Isua; early Earth history; Geological heritage

1. Introduction

There is much conjecture on early Earth's geodynamics, continental crust formation and the emergence of life – with particularly interest in life's origins extending to the general public. This conjecture and veil of uncertainty on the young Earth's first billion years of history (before 3550 Ma) is because the preserved geological record from those times is vanishingly small and largely of low fidelity. The reason for the limited extent of the earliest record is that over billions of years, most of Earth's ancient crust was destroyed from below by magmatism and from above by meteorite impacts, weathering and erosion. Consequently, >3550 Ma rocks form about one millionth of the present crust. A reason for the scarcity of information from Earth's surviving oldest rocks is that they were all subjected to ductile deformation and high temperature metamorphism in repeated, superimposed orogenic events (e.g., Nutman et al., 1996; Mueller and Nutman, 2017 and references therein). This destroyed much detail of the rock's original features, meaning that in most instances the record is of low fidelity and therefore only suitable for first-order conclusions on early terrestrial evolution via geochemistry and geochronology (e.g., Moorbath et al., 1972, 1973; Baadsgaard et al., 1986; Bennett et al., 1993, 2002, 2007; Polat and Hoffman, 2003; Dauphas et al., 2004; Izuka et al., 2007, 2009; O'Neil et al., 2016). As this article is intended to include readers with no specialist knowledge of deformed and metamorphosed rocks from the earliest part of Earth's geological record, 'specialist' terms are defined or explained (bracketed and in *italics*) where they are introduced.

An exception to the obliteration of detail in Earth's earliest preserved geological record is the Isua supracrustal belt and adjacent areas dominated by granitic *sensu lato* rocks at the northern end of the Itsaq Gneiss Complex of Greenland (Fig. 1; Nutman et al., 1996). This is because the combination of rare domains of sufficiently low ductile deformation *and* low metamorphic grade, means that *details* of the origin and evolution of the most ancient crust and upper mantle can be established. Although at Isua there are many km² where the plutonic features of 3620-3820 Ma granitic rocks are preserved (Fig. 1; e.g., Nutman et al., 1996, 1999; Crowley et al., 2001; Crowley,

2003), it is within the more heterogeneous and disrupted supracrustal rocks
(*sequences dominated by metamorphosed volcanic and sedimentary rocks, with minor intrusions*) that survival of this primary evidence is exceedingly rare. Thus as an approximation, unambiguous >3600 Ma sedimentary structures, stromatolites and volcanic structures (e.g., Allaart, 1986; Nutman et al., 1984, 2017, 2019 and references therein; Komiya et al., 1999; Fedo, 2000; Frei and Polat, 2007) are preserved in less than a millionth of the >3600 Ma rocks – thereby forming less than a trillionth of the entire global rock record! Nonetheless, this tiny, unique, part of the geological record contains important information on deep-Earth to atmospheric processes and everything else in between, including the ecological diversity of the earliest life record.

This paper gives a background and summary of five Isua area outcrops (Fig. 1), which should be preserved for a combination of scientific uniqueness and their historical legacy in the investigation of the early Earth:

- 1) Two small outcrops at a single locality, where ~3700 Ma stromatolites (*structures built by microbial communities*) have been reported by Nutman et al. (2016, 2019), but contested by Allwood et al. (2018). If the stromatolite interpretation is correct, then this is the earliest tangible (as opposed to isotopic) evidence of life on Earth.
- 2) The world's oldest unconformity, where a sequence of ~3710 Ma submarine volcanic rocks is overlain by a transgressive sequence of ~3700 Ma sedimentary rocks (e.g., Nutman and Friend, 2009). This unconformity is most clearly-exposed over only about 5m. As the world's oldest terrestrial 'stratigraphy' it is a notable geological feature.
- 3) A limited outcrop of ~3700 Ma detrital sedimentary rocks that contain micro-graphite flakes, whose carbon isotope signature is convincingly interpreted as indicating biomediation (Rosing, 1999). As one of two Isua earliest-life localities, this is another notable site worthy of protection.
- 4) The extensive occurrences of banded iron formation (*a special type of early Precambrian sedimentary rock*) at the edge of the Ice Cap. This is important

because it marks the realisation in the early 1970s (Moorbath et al., 1973) of the antiquity of the oceans, plus it is the best resource for understanding early Earth hydrosphere and atmosphere chemistry.

- 5) A small (few m³) body of ≥ 3800 Ma abyssal peridotite (*a rock derived from the upper mantle*) provides a unique insight into the chemistry of the deep Earth in deep time (e.g., Bennett et al., 2002).

We contend that for this less than a trillionth of the terrestrial rock record, ongoing studies should rely as much as possible on already collected material, and ultimately that some localities should have government protection. This is not only so that it still exists for future scientists who with their superior technology and extended knowledge will gain deeper insight into the early Earth, but also because it is a unique part of global heritage.

2. Geology of the Isua supracrustal belt and adjacent metaplutonic complexes

The 35 km long Isua supracrustal belt is the largest supracrustal rock unit within the Eoarchean (>3600 Ma) ~ 3000 km² Itsaq Gneiss Complex in southern West Greenland (Fig. 1; Allaart, 1976; see Nutman and Friend, 2009 for 1:20,000 scale geological map). The belt is bounded by metaplutonic complexes, with the one to the north consists of 3710-3685 Ma tonalite (*a type of K-poor granitic sensu lato rock*) protoliths cut by 3650-3640 Ma granite sheets (e.g., Nutman et al., 1996, Crowley et al., 2002; Crowley, 2003; Nutman and Friend, 2009) and the southern one dominated by 3820-3795 Ma tonalite protoliths. On the east the belt is obscured by the Inland Ice and to the west it is in tectonic contact with Mesoarchaeon rocks (3100-3000 Ma; Nutman and Friend, 2009 and references therein).

The Isua supracrustal belt contains two tectonically juxtaposed slices of unrelated supracrustal rocks ~ 100 million years difference in age (Fig. 1; e.g., Nutman et al., 1996, Crowley et al., 2002; Crowley, 2003; Kamber et al. 2005; Nutman and Friend, 2009). The belt's northern and median portions comprise ~ 3700 Ma assemblages and

its southern portion of the belt is a ~3800 Ma assemblage (Fig. 1; Nutman et al., 1996, Nutman and Friend, 2009). The metachert, banded iron formation (BIF) and dolostone ~3750 Ma *dividing sedimentary unit* (DSU) lies between the ~3700 and ~3800 portions (Nutman and Friend, 2009). The northern contact of the DSU with the ~ 3700 Ma assemblage is interpreted as an Eoarchean fault affected by later folding and metamorphism (Nutman and Friend, 2009). The ~3800 and 3700 Ma assemblages evolved separately from each other and were tectonically juxtaposed before 3660 Ma - the age of the first igneous intrusions common to both terranes (Crowley, 2003).

Within both the ~3700 and ~3800 Ma assemblages the dominant lithologies are amphibolites derived from diverse basaltic volcanic rocks, felsic volcanic rocks, and felsic volcano-sedimentary and chemical sedimentary rocks, particularly chert and banded iron formation (e.g., Allaart, 1976; Dymek and Klien, 1988; Nutman et al., 1984; Komiya et al., 1999; Polat et al., 2002; Polat and Hofmann 2003, Bohlar et al., 2004, 2005; Furnes et al., 2007; Jenner et al., 2009). Gabbros and ultramafic rocks are volumetrically minor. The ultramafic rocks were derived from both cumulates in gabbro intrusions (e.g., Dymek et al, 1988) and from tectonic slices of the upper mantle (Friend and Nutman, 2011).

Although Neoarchean deformation in the Isua supracrustal belt is low to moderate, most of the belt was strongly deformed in the Eoarchean (e.g., Bridgwater and McGregor, 1974). Thus, the compositional layering in the volcanic and sedimentary rocks is mostly of transposed tectonic origin, meaning that original volcanic and sedimentary features of the rocks are only rarely preserved (e.g., Nutman et al., 1984; Myers, 2001). Commonest original structures are pillows within submarine volcanic rocks, and to a lesser extent, bedding in banded iron formation and graded bedding in felsic volcano-sedimentary rocks (e.g., Nutman et al., 1984; 2017; Komiya et al., 1999; Solvang, 1999; Furnes et al., 2007). Preservation of primary structures in easily-deformed carbonate-rich sedimentary lithologies is extremely rare (Nutman et al., 2016, 2019), and have been contested by other workers (Allwood et al., 2018). All Isua supracrustal belt rocks have been repeatedly metamorphosed, with the maximum grade ranging from lower amphibolite (500-550°C) to middle amphibolite facies (up

to 650°C; Rollinson, 2003).

3. Five nominated localities

3.1. ~3700 Ma stromatolites and associated shallow water sedimentary structures

Pockets of preserved primary structures in the Isua supracrustal belt are commonest in the area around the locality (65°10.74'N 49°48.25'W; WGS84 datum) of stromatolites (Fig. 1) proposed by Nutman et al. (2016, 2019), but questioned by Allwood et al. (2018). This unique preservation is because this area contains several Eoarchean isoclinal folds (*folds where the long sides of the fold are approximately parallel*), in the cores of which there are unusual areas of lowest deformation permit the highest possibility of pre-tectonic sedimentary and volcanic structures of being preserved.

In the vicinity of the stromatolite locality, relict pillow structures in meta-volcanic rocks plus conglomerate structures in meta-sedimentary rocks have been known for decades (Fig. 1; Allaart, 1976; Nutman et al., 1984; Appel et al., 1998; Komiya et al., 1999; Solvang, 1999). Some of the volcanic structures reported by Appel et al. (1998) and Solvang (1999) are in the same fold core as the stromatolites, and <100 m distant from them. Associated with the volcanic rocks near the stromatolite locality are layered quartz + tremolite ± carbonate rocks with modern Earth seawater-like REE+Y (rare earth element + yttrium) trace element signatures (Friend et al., 2008). In the early 2010s with the melting of a decades-old snow patch, the strongly deformed quartz + tremolite ± carbonate meta-sedimentary rocks reported by Friend et al. (2008) were traced to a low deformation area in the fold core, where there are small relicts of sedimentary structures and the stromatolites proposed by Nutman et al. (2016) occur (Fig. 2). The reported stromatolitic carbonates occur as part of a mapable stratigraphic succession that can be traced around several fold structures in the eastern part of the Isua supracrustal belt (Nutman and Friend, 2009; Nutman et al., 2019).

In outcrops surrounding the proposed stromatolite occurrences, coarse metamorphic recrystallisation caused by reaction between quartz and carbonates to forming calc-silicate minerals (with/without high deformation) has completely erased

primary structures (e.g., Fig. 3A). However, in other domains where hydrous fluids have not infiltrated the rocks, the lack of reaction between quartz and carbonate has retained well-preserved primary structures.

Not only the stromatolites (proposed by Nutman et al., 2016, 2019 but contested by Allwood et al., 2018), but also cross-bedded quartz-rich + dolomite sandstones (Fig. 3B), and two units of angular conglomerate (*tempestites; probably formed by storm-wave action*) are all preserved in overturned bedding within the core of the fold. Classic structural geology texts (e.g., Ramsay and Huber, 1987) explain that the preservation of stromatolites and other associated primary features is consistent with their location in the plane of close no finite strain that exists in the core regions of buckle folds.

Preservation of proposed stromatolites was extremely fortuitous, as strong recrystallization of the bedded dolomites occurs ~1 m directly along strike of the preserved stromatolites. Stromatolites have been proposed on two outcrops. On the first they form at least 4 horizons, and possibly occur in another two, where they are smaller and less well defined. As described in the original paper (Nutman et al., 2016), the stromatolites vary from steep-sided, commonly slightly asymmetric coniform shapes, from 1-3 cm in height, rising up from a flat basal horizon (Fig. 3C). On the second outcrop, the stromatolitic dolomite unit that immediately overlies an edgewise conglomerate and is capped by a 3-5 cm thick bed of quartz-rich sandstone that displays cross-bedding (Fig. 3D) and has a basal component that fills troughs between adjacent stromatolite cones. Critically, the top of the quartz sandstone fill is flat and overlain by a second quartz-rich unit sandstone unit that has a slightly different composition.

However, the sedimentary and biogenic interpretation of all these structures has been questioned by Allwood et al. (2018). These authors propose instead that all the structures we have described originated by deformation, metamorphism and the infiltration of carbonate bearing fluids after the rocks formed at 3700 Ma, and therefore give no direct information on surface conditions, including any evidence of ancient life. In this ongoing debate, Nutman et al. (2019) have responded by a more

detailed examination of the proposed stromatolites and related structures, to support their original brief report.

Clearly, the interpretations of these outcrops are contentious, with significant outcomes concerning not only for seeking earliest evidence of life on Earth, but also with a broader ramification concerning the fidelity of information that can be extracted from the Earth's oldest geological record. The outcrops containing the proposed stromatolites are very small, and it is important that they remain intact, at least until the debate exemplified by the Nutman et al. (2016, 2019) and Allwood et al. (2018) is resolved in the broader geological community.

In this context, Figure 4 documents the state of the stromatolite 'A' outcrop, less than one year after it was presented in the literature. On the left-hand side of this figure is our 2012 sampling, where we carefully removed a narrow slab, with zero wastage. Also, we deliberately avoided what we interpret as some of the most spectacular stromatolites in the middle portion of the outcrop, realising that they should be left intact for all future visitors to study. The figure demonstrates the state of the right hand side of the outcrop in July 2017, where much of the removed rock was discarded at the foot of the outcrop.

3.2. Discovery locality of ~3700 Ma ¹³C-depleted graphite of biogenic origin

In the ~3700 Ma volcanic and sedimentary rocks in the northwestern end of the Isua supracrustal belt, there are tectonic slices of felsic-intermediate schists intercalated with units of amphibolites (Fig. 1). In one outcrop (65°09.42'N 50°08.16'W), sedimentary layering is preserved in the felsic-intermediate schists. This outcrop was first recognised to have relict sedimentary layering by V.R. McGregor and D. Bridgwater in the early 1970s (the late V.R. McGregor, personal communication, 1980). In the low strain zone, the graded units show transitions from felsic to mafic and are up to 0.5 m thick (Fig. 5A). The bases of the graded units are sharp. Packets of several graded felsic layers are common and locally contain clasts of mafic pelitic material (Fig. 4e of Nutman et al., 1984).

The key interest in this outcrop is that it is one of Isua's early life localities. Rosing

(1999) reported the presence of ^{13}C -depleted micro-graphite flakes (Fig. 5B). These were interpreted to have been derived from biogenic reduced carbon via the superimposed metamorphism. This first study was based on random graphite flakes in the rock's matrix. Subsequent studies on the graphite nano-structure from a locality along strike (Ohtomo et al., 2014) and the reporting of graphite as inclusions locked in garnet (Hassenkam et al., 2017) have further strengthened the biogenic origin for the carbon of this graphite. Therefore, this outcrop should be protected, because globally it is a key early life locality, combined with the preserved sedimentary structures discovered in the 1970s by McGregor and Bridgwater. Protection would not stifle additional early life research using these rocks, because up the hill to the south for at least 100 m, the same unit outcrops, albeit the deformation is a bit more intense.

3.3. ~3700 Ma unconformity with weathered volcanic rocks overlain by conglomerates

Known about and discussed from the 1970s (Allaart, 1976) is an outcrop of schist crowded with prominent quartz clasts (*conglomerate* on Fig. 1; 65°10.15'N 49°49.42'W)). This is one of the most visited localities in the Isua supracrustal belt and has elicited much discussion and diametrically opposed interpretations. The most widely held view, supported by the summary below and the detailed appraisal by Fedo (2000) is that its protolith is a genuine sedimentary rock, whereas a single dissenting interpretation is that it is an entirely tectonic feature (Myers, 2001). This lithology is not unique to this one locality, because it crops out at other stratigraphically and structurally equivalent sites at several other places in the northeastern end of the belt (Nutman et al., 1984).

The (metamorphosed) conglomerate (Fig. 6A) has clasts of biotite-amphibolite, coarse-grained polycrystalline quartz, and rare layered chert, in a biotite-rich matrix. The biotite-amphibolite clasts are regarded as altered (weathered) mafic volcanic rocks (Nutman et al., 1984; Fedo, 2000). At one side, the conglomerate is in sharp contact with fine-grained massive biotite-rich garnetiferous amphibolites (contact indicated by red arrow in Fig. 6B). Given their altered chemical composition and

elevated $\delta^{18}\text{O}_{(\text{VSMOW})}$ value of +16.6, these rocks are interpreted as basaltic rocks affected by low temperature alteration (Nutman et al., 2017). On its other side, the conglomerate is in sharp contact with fine-grained layered dolomite and dolomite + quartz sedimentary rocks (Fig. 6C). At this locality, there is *no* apparent shearing on both contacts of the conglomerate and *no* change in the aspect ratio of the conglomerate's quartz clasts. This indicates that here, the boundaries of the conglomerate are not tectonic breaks, and it appears that there is not even a significant deformation gradient across them. Therefore, both contacts are original; an unconformity with underlying altered metabasalts/andesites and a conformable sedimentary one with overlying dolomite and dolomite + quartz rocks (Nutman et al., 2017). The significance of this locality is that it incorporates not only the earliest defensible unconformity in the global geological record, but also displays perhaps the oldest recognisable detailed stratigraphy of conglomerates and then sandstones deposited over a volcanic surface already weathered at ~3700 Ma (Nutman et al., 2017a).

The concern about this highly significant locality is the small extent of outcrops where the relationships are displayed without obliteration by later deformation. Thus, the unconformity at the base of the conglomerate is exposed over only <5 m. Additionally, there has been major quarrying of the best exposure of the conglomerate, particularly via a large block of at least 1 ton removed for a museum display late last century (Fig. 6D). This site, which is unique in the world for marking the point in time for Hutton's 'no vestige of a beginning' with a preserved stratigraphy including even an unconformity, should be preserved for both heritage and scientific purposes.

3.4. ~3700 Ma Iron Mountain banded iron formation

Via a massive positive aeromagnetic anomaly due to a large amount of banded iron formation (BIF) concentrated at the eastern end of the belt (Fig. 7A; around 65°12.73'N 49°44.93'W), the Isua supracrustal belt was discovered in the 1960s by the prospecting company Kyrolitselskabet Øresund A/S (Keto, 1970; *BIF; Iron Mountain* on Fig. 1). A game-changer for understanding not only the Isua

supracrustal belt but also the nature of the early Earth was the first Pb-Pb isochron work undertaken on the Isua BIF, which gave an age of 3760 ± 70 Ma (Moorbath et al., 1973). This was important on two counts; firstly, it established the extremely old Eoarchean age of Isua's (meta)sedimentary rocks and secondly because BIF is a water-lain sedimentary rock, this also demonstrated that very early in Earth's history there was a retained hydrosphere – making the very early establishment of life feasible. Within this millennium evidence of an early retained hydrosphere has been extended back into the Hadean (>4000 Ma) as the 'cool early Earth' (Valley et al., 2002).

A key locality for this landmark for understanding of the early Earth is the large 'Iron Mountain' exposure of BIF at the extreme northeastern end of the Isua supracrustal belt at the edge of the Ice Cap (Figs. 1 and 7A). This is the broadest outcrop of BIF in the belt, because it is repeated by refolding of early isoclinal folds in the hinge of a later Eoarchean fold (map in Nutman and Friend, 2009). Within this structural location, there are areas where the original sedimentary layering is preserved (albeit buckled by folding; Frei and Polat, 2007), and details such as pre-tectonic diagenetic chert nodules are preserved within it (Fig. 7B).

There are vast amounts of relatively well-preserved BIF at the Iron Mountain, thus it will never be threatened by sampling for scientific purposes, but it could be removed by mining. Over the last 4 decades since Kyrilitselskabet Øresund A/S relinquished their exploration lease, several other companies have undertaken new assays and scoped the logistics for mining. However, because of the remoteness of the Isua and the current domination of the iron ore market by massive accessible deposits in Australia and Brazil, Isua BIF remains uneconomic. If iron ore mining did start at Isua, the first target would be the large exposures at Iron Mountain. This mountain presents the world's best scientific repository of earliest Precambrian BIF plus it has historical significance as being where for the first time the 'normality' of the early Earth became apparent via evidence of an ocean at 3700 Ma. Our hope is that mining of Iron Mountain never occurs, preserving it for future generations.

3.5. ~3800 Ma mantle rocks (*dunite-harzburgite*)

Samples of the mantle dunite and harzburgite (>90% *olivine and olivine + orthopyroxene rocks respectively*) exposed for study at the surface of the Earth are exceedingly rare, even in the Phanerozoic. Additionally, when (dry) mantle rocks are tectonically interdigitated with (wet) crustal rocks within orogenic belts, they undergo severe hydration to give amphibole-, serpentine-, talc-bearing magnesian schists, typically with significant chemical alteration as well. This is the commonest state of Eoarchean ultramafic rocks that are found as lenses both within the Isua supracrustal belt and within the adjacent areas dominated by granitic rocks (e.g., Allaart, 1976, Nutman et al., 1984, 1996; Dymek et al., 1988; Friend et al., 2002; Friend and Nutman, 2011). Geochemical and mineralogical studies to identify the origin of these schists indicate they were derived from three sources; olivine-rich lower parts of basaltic flows, peridotites from lower parts of layered gabbro intrusions and from slices of the upper mantle (Allaart, 1976; Dymek et al., 1988; Nutman et al., 1996; Friend et al., 2002; Friend and Nutman, 2011; Rollinson, 2007; Kaczmarek et al., 2016). Some of the larger occurrences of these schists contain kernels of less hydrated rocks, where pre-metamorphic olivine is preserved as the main phase, and where the whole rock geochemistry (such as the locus of analyses in an Mg/Si versus Al/Si plot, Fig. 8A) indicate they are relicts of variably-depleted upper mantle. It can be demonstrated that these olivine-bearing ultramafic rocks are Eoarchean in age, because they are all intruded by the ~3500 Ma Ameralik dykes, and in some instances by veins of Eoarchean granitic rocks, dated by the U-Pb zircon method (Nutman et al., 1996; Friend et al., 2002).

There are two main occurrences of note of these upper mantle rocks. The first is of ≥ 3710 Ma examples in the northwestern end of the Isua supracrustal belt. These occur as two large (>100 m long) olivine-rich kernels within lenses of ultramafic schist (dunites 'A' and 'B' on Fig. 1). In these kernels the rocks are dunite – harzburgite, in which olivine is variably replaced by serpentine, but nonetheless pre-metamorphic mantle minerals are preserved (Friend and Nutman, 2011). Olivines in this occurrence have microfabrics of a class only known from mantle wedges below (younger)

suprasubduction ophiolite assemblages (Kaczmarek et al., 2016). There are enough of these rocks present, such that they will never be depleted by sampling for science.

The other assemblage of relict mantle rocks occurs as inclusions within the granitic rocks to the south of the Isua supracrustal belt, with for example a 3804 ± 3 Ma sheet intruded into dunite (Nutman et al., 1996; Crowley, 2003; Fig. 1). In this instance, the volume of preserved olivine-rich rock is much smaller than the 100 million year younger examples in the Isua supracrustal belt described above. Also, they occur as small kernels within numerous scattered ultramafic bodies, rather than as larger kernels within two bodies. Of particular note is the small ($\sim 1 \text{ m}^3$) pod first collected as G93/42 in 1993 (Fig. 8B; $65^\circ 01.32' \text{N}$ $50^\circ 12.92' \text{W}$). This rock is a remarkably unaltered harzburgite, with the most limited degree of grain boundary alteration, and with the preservation of intra-olivine spinel grains. Comprehensive mineral and whole rock chemistry were reported on this sample by Friend et al. (2002). Re-Os isotopic analysis was undertaken on olivines and spinels extracted from this sample, resulting in $^{187}\text{Os}/^{188}\text{Os}_{(3800 \text{ Ma})}$ of 0.1021 ± 0.0002 and 0.1009 ± 0.0002 (Bennett et al., 2002). These data extend direct measurement of Os isotopic compositions to much earlier periods of Earth history than was previously reported and provide the best constraints on the Os isotopic composition of the early terrestrial mantle. Bennett et al. (2002) also highlighted that the 3800 Ma mantle peridotites have not only chondritic $^{187}\text{Os}/^{188}\text{Os}$ compositions but also Os concentrations similar to the mean abundances measured in modern peridotites. This places an upper limit on the timing of a late accretionary veneer. Over the past 2 decades the G93/42 locality has been revisited and resampled by several research teams (e.g., Van der Locht et al., 2018), with the replication of the measurements and conclusions of Bennett et al. (2002). We stress that this is the key locality for pinning evolution of the Re-Os isotopic system and Platinum group element mantle budgets on Earth in deep time. Even when the authors sampled it in 1993 the volume of available material was small. Samples from this locality that will suffice all researchers' needs into the foreseeable future. Therefore, we suggest that additional sampling of the G93/42 site should be avoided.

4. Discussion

4.1. Saving the deep time rock record for future science?

Marring of famous outcrops is always inadmissible, whether it be for science or for souvenirs. Two examples are the igneous cumulate layering of the Skærgaard gabbro intrusion illustrated by Wager and Deer (1939), that came to grace the desk of a University Professor in the 1970s (see exposé by Bridgwater et al., 1978) and diamond drill core sampling scattered around the Ediacaran golden spike locality in the Flinders Ranges of South Australia (Fig. 9). In both cases, adjacent outcrops ~10 m along strike could have just as well been sampled. For the resampling of the proposed Isua stromatolites, two extra factors are paramount. Firstly, they are only known to be exposed on ~3m² of rock, unlike something such as, for example, the classic Skærgaard graded igneous layering, which occurs over several km².

There are more Lunar samples available than some of the Isua area key resources such as the proposed stromatolites or the G93/42 harzburgite. These Isua resources should be treated with an equal degree of care and reverence as Lunar samples. We hope that they can remain available for future generations – if necessary with government protection, as for example has now been afforded by the relevant local jurisdictions for the komatiites of Komati Gorge and the ‘Trendall Locality’ Strelley Pool Chert Formation stromatolites of the Pilbara.

4.2. The scientific and societal benefits

For most of these sites, their significance goes beyond the realms of scientific research, because they relate to the historical understanding of the early Earth and demonstrate concrete geological and geochemical evidence that the origin of life on Earth is extremely early, certainly within the first 500 million years. This is particularly important for other scientific disciplines such as Astrobiology, because it indicates communities of microbial organisms can arise within the timeframe of Mars’ early wet period (late Noachian). As such, these sites should be preserved as heritage for all in the future. Additionally, if preserved with no further damage, they do open-up the possibility of geo-tourism.

5. Conclusion

The Isua area of Greenland contains some geological sites which provide a unique insight into the early Earth and the antiquity of life. For those of very small extent, particularly the proposed stromatolites, further work should rely as much as possible on already collected samples, and hopefully they can eventually be protected by government, as has been achieved for other parts of the earliest geological record, for example, in Western Australia.

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Figure Captions

Figure 1. Summary geological map of the Isua supracrustal belt and adjacent gneisses, showing discussed localities.

Figure 2. The proposed stromatolite outcrops ('A' and 'B') viewed from the northwest. The outcrops were until recently covered by a perennial snowpatch, the border of which is indicated.

Figure 3. Low deformation area where ~3700 Ma sedimentary structures are preserved (stromatolite site on Fig. 1). (A) Finely-laminated quartz + dolomite rock cut discordantly by a recrystallisation front (red arrow) caused by hydration, with the growth of course-grained tremolite (left side of image) destroying the sedimentary structure. (B) Cross-bedded quartz + dolomite sandstones. (C) Stromatolites at the Nutman et al. (2016) site 'A'. (D) Cross-laminated quartz + dolomite sandstones overlying a massive dolostone, the top of which is marked by small stromatolites (site 'B' of Nutman et al., 2016).

Figure 4. Stromatolite site 'A' sampling. To left is our 2012 sampling, with material available on loan for collaborative study. To the right is the sampling found in July 2017, with large amount of wastage (buried in ice at outcrop base) and numerous saw cuts. Structures are inverted due to being overturned in a fold.

Figure 5. (A) Discovery outcrop of ~3710 Ma relict sedimentary layering, probably representing distal turbidites deposited in deep water. (B) Summary histogram showing $\delta^{13}\text{C}$ values of graphite flakes from rocks shown in (A).

Figure 6. (A) General overview of the round pebble conglomerate where volcanic clasts are best preserved. (B) Unconformity (indicated by red arrow) below the conglomerate (Figure 1) top and left, with underlying altered basaltic-andesitic volcanic rocks bottom and right. (C) Interlayered dolostone (brown) and quartz+dolomite rocks (off-white) at the conglomerate locality. At bottom of the image (partly obscured by debris) the contact between the conglomerate and the dolomite-quartz rocks is marked by a red arrow. (D) Site where large block of conglomerate has been removed for a museum display. Pen for scale on all frames.

Figure 7. (A) The Iron Mountain at the northeastern exposures of the Isua supracrustal belt, consisting entirely of ~3700 Ma BIF. (B) Detailed of preserved diagenetic / sedimentary structures preserved in the Iron Mountain BIF. Shown are chert nodules encapsulating Fe-silicates, in a fine-grained quartz + magnetite matrix (see explanation in Nutman et al., 2017b).

Figure 8. (A) Mg/Si versus Al/Si plot for Isua area dunite-harzburgite bodies interpreted to be of mantle origin. Indicated is sample G93/42, discussed in detail. (B) G93/42 outcrop, as seen in 1997.

Figure 9. Needless damage to the Ediacaran ‘golden spike’ outcrop in the Flinders Ranges, South Australia.

High strain & altered

'A'

Low strain

'B'

Snowpatch extent

2012

2016/
2017

A

B

EDIACARAN

GSSP

2004