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REPLY

10.1029/2021TC007148

This article is a reply to a comment by Nutman et al. (2022), https://doi.org/10.1029/2021TC007036.

Key Points:

- Neoarchean tectono-metamorphism is viable and may be the only deformation event. It would likely involve (proto-)plate tectonics
- All prograde metamorphic records can be interpreted as amphibolite facies
- Isua Eoarchean crustal formation is feasible within a heat-pipe tectonic context

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Reply to Comment by A.P. Nutman et al. on "Tectonics of the Isua Supracrustal Belt 1: P-T-X-d Constraints of a Poly-Metamorphic Terrane" by A. Ramírez-Salazar et al. and "Tectonics of the Isua Supracrustal Belt 2: Microstructures Reveal Distributed Strain in the Absence of Major Fault Structures" by J. Zuo et al.

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Abstract Structural and metamorphic analyses from the works under discussion (Ramírez-Salazar et al., 2021, https://doi.org/10.1029/2020tc006516; Zuo et al., 2021, https://doi.org/10.1029/2020tc006514) show that the Isua supracrustal rocks can be interpreted to record one single deformation and metamorphic event featuring quasi-homogeneous deformation and amphibolite facies metamorphism, followed by late static retrogression or thermal event(s). Observed deformation and metamorphic records are consistent with three hypotheses: (a) they represent Neoarchean plate tectonic overprints following Eoarchean plate tectonic evolution (e.g., Nutman et al., 2022, https://doi.org/10.1029/2021TC007036); (b) they represent Eoarchean heat-pipe and/or plate tectonic deformation that survived later tectonic event(s) (e.g., Ramírez-Salazar et al., 2021, https://doi.org/10.1029/2020tc006516; Zuo et al., 2021, https://doi.org/10.1029/2020tc006514), and; (c) they represent one major Neoarchean tectonic event, such that the Isua supracrustal belt (ISB) records Eoarchean protolith-related processes but does not record Eoarchean metamorphism nor deformation. While a heat-pipe model for crustal formation is central to hypothesis 2, it is also a viable crustal formation mechanism for hypothesis 3 where the ISB would still form in a heat-pipe setting in Eoarchean time, but the major deformation of the heat-pipe lithosphere happened during Neoarchean time, probably by (proto-)plate tectonic processes. If the data presented in Zuo et al. (2021), https://doi.org/10.1029/2020tc006514 and Ramírez-Salazar et al. (2021), https://doi.org/10.1029/2020tc006516 only reflect Neoarchean histories, then these cannot be used to refute or support any Eoarchean geodynamic background for the formation of the ISB.

1. Introduction

We thank A. P. Nutman, C. R. L. Friend, and V. C. Bennett for the opportunity to work alongside them in this Comment and Reply venue and beyond, to further develop new knowledge of this special terrane for understanding early Earth.

Nutman et al. (2022) argue that in our prior works, particularly Ramírez-Salazar et al. (2021) and Zuo et al. (2021), we have made errors and omissions, and thereby erroneously advanced a heat-pipe tectonic interpretation whilst missing diverse indicators of plate tectonics. Our published works argue for quasi-homogeneous amphibolite facies metamorphism and strain distribution across the Isua supracrustal belt (ISB) resulting from a single dominant Eoarchean event, whereas they interpret strongly heterogeneous Eoarchean metamorphism and deformation prior to a widespread Neoarchean tectonothermal overprint. In contrast, we suggest a model in which pre-deformation assembly of the main Isua lithologies was accomplished via magmatism and deposition in a heat-pipe cooling context, whereas Nutman et al. (2022) argue that the belt was assembled via Eoarchean plate tectonic collision as recorded by a suture preserved along the length of the belt. We emphasize at this point that the focus

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of our published Isua work is not to uniquely demonstrate heat-pipe tectonics there. Rather, the point is to explore whether non-plate tectonic models might be viable for Isua.

In this contribution, we acknowledge key constraints that we had not fully considered which Nutman et al. (2022) highlight. We accept their argument that Neoarchean metamorphism and deformation may have had a stronger imprint on the ISB than we had previously acknowledged. However, we disagree with most of their critiques of our works and present clarifications of these disagreements. We show that the tectonic model proposed by Nutman et al. (2022) is not the only possible model and other tectonic evolutionary pathways (e.g., Ramírez-Salazar et al., 2021; Zuo et al., 2021a) remain viable in view of currently available data.

Responses (below) follow the section organization of Nutman et al.'s (2022) Comment.

2. Ages and Origins of Petrofabrics of the Isua Supracrustal Rocks and the Ameralik Dikes

We agree with Nutman et al. (2022) that the co-linearity between the petrofabrics of the Ameralik dikes and the Isua supracrustal rocks likely indicates a Neoarchean tectono-thermal event that has affected both the ISB and the dikes. As Nutman et al. (2022) articulate, one viable possibility is that the observed petrofabrics in the Isua region may represent Neoarchean overprints of Eoarchean plate tectonic petrofabrics, with the Eoarchean deformation being preserved in sparse outcrops across this region. However, other two possibilities are viable: (a) the petrofabrics in the Isua supracrustal rocks may reflect Eoarchean processes that survived Neoarchean tectonism; or, (b) they may be solely Neoarchean, and thereby would not constrain any potential Eoarchean tectonics across the ISB. To explain why, we first review key geology. We then describe these three possibilities and how they remain viable (cf. Nutman et al., 2022).

The Ameralik dikes preserve diverse deformation overprints and cross-cutting relationships with respect to the host ISB rocks (Figure 1) and have been investigated dominantly in three areas (Figure 1; e.g., Crowley et al., 2002; Nutman, 1986; Nutman et al., 1983, 2015; White, Crowley, & Myers, 2000): (a) central part of the northern meta-tonalites (Area A in Figure 1); (b) central part of the ISB and adjacent northern meta-tonalites (Area B in Figure 1); and (c) northeastern part of the ISB (Area C in Figure 1). In Area A, the dikes are mostly undeformed. In Areas B and C, abundant dikes have been reported as preserving foliation, folds and/or steeply SE plunging amphibole and/or plagioclase stretching lineations (Crowley et al., 2002; Nutman, 1986; Nutman et al., 2022; White, Crowley, & Myers, 2000). These lineations are generally parallel to minor fold axes and lineations in the ISB (e.g., Nutman, 1986; Nutman et al., 2022). Nonetheless, some deformed dikes in Areas B and C still cross-cut earlier foliation and folds in the ISB (Figure 1; Crowley et al., 2002; White, Crowley, & Myers, 2000). In addition, in Area B some undeformed dikes cross-cut the folded northern edge of the ISB (Figure 1; Figure 9 of Crowley et al., 2002). In the western ISB, arguably undeformed dikes that are concordant to the deformed host ISB rocks preserve relict igneous textures (Figure 1; Figures 2g and 2h of Furnes et al., 2007; Friend & Nutman, 2010). Ameralik dikes are reported to have experienced epidote-amphibolite facies metamorphism ($\leq$550°C) with garnets present within a few dikes in the ISB and some dikes in the southern meta-tonalites (e.g., Gauthiez-Putallaz et al., 2020; Nutman, 1986). Zircons and baddeleyites separated from the Ameralik dikes in the Isua area yield U-Pb ages ranging from ~3,570 to ~2,400 Ma (Figure 1a; e.g., Nutman et al., 2004, 2007, 2015; White, Crowley, Parrish, & David, 2000). Several dikes from Area A yield an Sm-Nd orthopyroxene + plagioclase + whole-rock isochron of ~3,410 Ma (Figure 1; Nielsen et al., 2002).

Additional key observations and interpretations made on rocks from the Isua region are: (a) crystallization ages of three granitoids (GGU225919, deformation unknown; G07/20 deformed; and G97/43, deformed) that cross-cut the deformed supracrustal rocks have been interpreted as ~3,570, ~3,660 and ~3,610 Ma, respectively (SHRIMP U-Pb zircon ages; Nutman et al., 1997, 2002, 2009); (b) several deformed granites/pegmatites in the meta-tonalites near the ISB yield ages of ~3,660 to ~3,600 Ma (SHRIMP U-Pb zircon ages, e.g., Nutman & Friend, 2009; Nutman et al., 2002, 2013; and TIMS U-Pb zircon ages, Crowley et al., 2002; Crowley, 2003) (c) syn-tectonic garnets preserved in the ISB have been interpreted to record 550°C–650°C amphibolite facies metamorphism and correlated with mineral and/or whole-rock ages (Pb-Pb ages or titanite U-Pb ages) of >3,600 Ma (e.g., Crowley, 2003; Crowley et al., 2002; Gauthiez-Putallaz et al., 2020; Rollinson, 2002, 2003); (d) the post-tectonic garnets in the ISB have been interpreted to reflect $\leq$ 550 °C amphibolite facies metamorphism at ~2,850 Ma (mineral + whole rock Sm-Nd isochrons; Gruau et al., 1996; Rollinson, 2003) or ~2,690 Ma (zircon ages; Nutman

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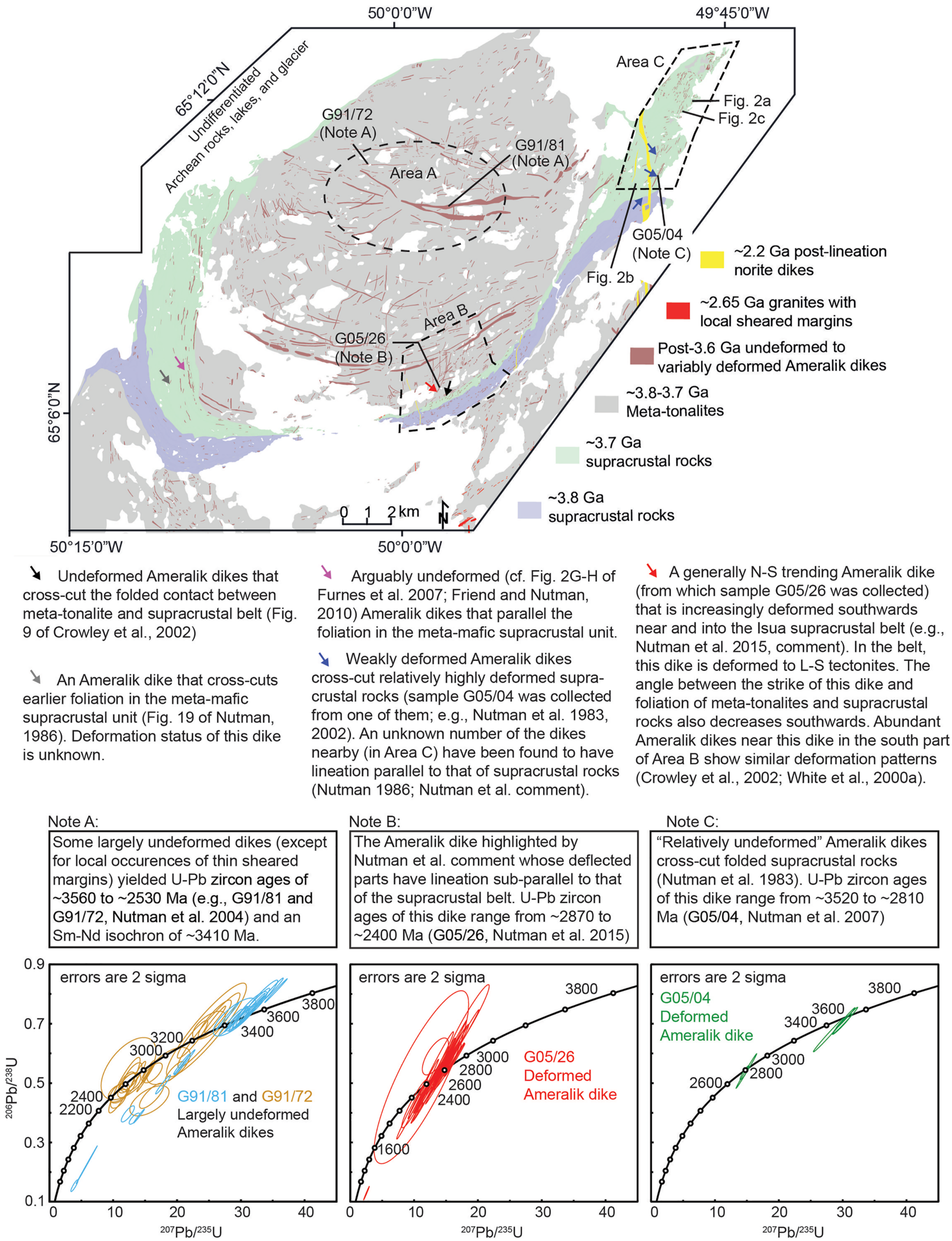

Figure 1.

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& Collerson, 1991; Nutman et al., 2022); and (e) Neoarchean timing of a regional tectonic event has been interpreted from ∼2,690 Ma zircon (re-)crystallization ages from ISB rocks and shear zones located >10 km south of the ISB (e.g., Nutman et al., 2015, 2022; Nutman & Collerson, 1991; Nutman et al., 2015, 2010, 2022), ∼2,650–2,600 Ma U-Pb titanites ages from rocks located ∼2–∼10 km south of the ISB (Crowley, 2003), ∼2,530 Ma zircon ages of the late-kinematic Qorqut granites (Nutman et al., 2010), and ∼2,200 Ma zircon ages (Nutman et al., 1995) of mostly undeformed norite dikes (Figure 1; Nutman, 1986; Nutman & Friend, 2009).

Based on above observations and interpretations, Nutman et al.'s works (e.g., Nutman, 1986; Nutman et al., 2002, 2013, 2015, 2015, 2022; Nutman & Friend, 2009) propose that the ISB experienced multi-phased metamorphism and deformation via plate tectonics before 3,600 Ma. Ameralik dikes intruded during ∼3,500 to ∼2,750 Ma (e.g., Nutman et al., 1983, 2002; 2007, 2022), with the Sm-Nd isochron (Nielsen et al., 2002) and oldest zircon ages of each dated dike representing crystallization ages (younger ages representing alteration or overgrowths; Figure 1, e.g., Nutman et al., 2004), During a Neoarchean terrane collision event the ISB and Ameralik dikes were deformed and metamorphosed together (e.g., Nutman et al., 2015, 2022, 2010). Strain partitioning during this event resulted in the local development of deformation features such as L-S fabrics in the Ameralik dikes, and overprinting of most of the ISB Eoarchean petrofabrics (Nutman, 1986; Nutman et al., 2022). Their model is viable under the following assumptions: (a) the post-tectonic garnets preserved in many Isua supracrustal rocks are either younger than ∼2,690 Ma (cf. Gauthiez-Putallaz et al., 2020; Rollinson, 2002) or are only preserved in areas that were isolated from the ∼2,750 to ∼2,530 Ma strain, (b) some of the pre/syn-tectonic garnets reflect Neoarchean metamorphism (cf. Rollinson, 2002, 2003); and (c) metamorphic assemblages associated with the post-tectonic garnets in the ISB record a southward increase of metamorphic temperatures (cf. Ramírez-Salazar et al., 2021) as interpreted from the Ameralik dikes (e.g., Nutman, 1986). Currently, we lack sufficient data to examine the validity of above assumptions.

An alternative tectonic evolution has been put forward by our group (Ramírez-Salazar et al., 2021; Webb et al., 2020; Zuo et al., 2021): In this model, the ISB and tonalites were formed by heat-pipe tectonics before ∼3,700 Ma. The ISB and parts of the tonalites were deformed and metamorphosed during a single progressive event predating the <3,500 Ma intrusion of the Ameralik dikes which cross-cut the Eoarchean sheath fold structures. Deformation was broadly coeval to amphibolite facies metamorphism and mostly accomplished by ∼3,600 Ma (this minimum age was interpreted from the titanite ages and proposed crystallization ages of granites that cross-cut the deformation fabrics, see above). Finally, the Isua area experienced Meso- and Neoarchean retrogression or mid-grade metamorphism, with associated deformation being weak to absent across the already highly deformed ISB. Such an evolution pathway is viable under an assumption that the ISB did not record or escaped any Neoarchean strain, and the Ameralik dikes concentrated the strain and developed Neoarchean linear fabrics that are sub-parallel to the Eoarchean linear fabrics in the ISB rocks (a scenario that has been proposed by James, 1976, and which might be possible if fluids or heat from the dikes localized the deformation; e.g., Nyman, 1999). This particular scenario—that two tectonic events would produce similarly-oriented linear fabrics – has been reported in other settings (e.g., Şengör et al., 2019) and in some places dikes do concentrate strain (e.g., Nyman, 1999; Scott, 2019).

Information highlighted by Nutman et al. (2022) and our data synthesis permits consideration of a third hypothesis. Because the petrofabrics of the Isua supracrustal rocks could reflect only one major tectonic event (see below, also Webb et al., 2020; Ramírez-Salazar et al., 2021; Zuo et al., 2021; cf.: Nutman et al., 2002, 2022; Gauthiez-Putallaz et al., 2020; Rollinson, 2002), the Isua supracrustal rocks and Ameralik dikes may only record one major Neoarchean event, which produced all the observable structures and syn-tectonic metamorphic records in the Isua area. Variably cross-cutting relationships between the Ameralik dikes and folded supracrustal rocks, suggest intrusion throughout the deformation event. This third possibility is viable if: (a) Eo-to Mesoarchean U-Pb ages of zircons from Ameralik dikes represent inherited ages (±Pb-loss), and the Neoarchean zircon ages

Figure 1. Geological map with deformation patterns for post-3.6 Ga rocks, including the Ameralik dikes and associated U-Pb zircon geochronology represented in Concordia diagrams. The Ameralik dikes are highlighted with a pale brown color. Deformation patterns of the Ameralik dikes are summarized from the literature (e.g., Nutman et al., 1983, 2002, 2015, 2022; Crowley et al., 2002; Nutman, 1986; White, Crowley, & Myers, 2000). Arrows show the locations (corresponding to the arrow tips) of the Ameralik dikes that have been specifically noted in the literature. Different colors correspond to different deformation patterns. Areas A and B are places where some deformation observations were made for the associated Ameralik dikes. Area A follows Figure 1 of White, Crowley, and Myers (2000) and Figure 2 of Crowley et al. (2002). Area B follows Figure 1 of White, Crowley, and Myers (2000). Area C follows Figure 23 of Nutman (1986) and Figure 1 of White, Crowley, and Myers (2000). The age information of the Ameralik dikes is compiled from Nielsen et al. (2002) and Nutman et al. (2004, 2007, 2015). The locations of field photos in Figure 2 are highlighted with black lines.

represent dike crystallization (±Pb-loss) (Figure 1a); (b) the >3,500 Ma zircon ages of granite/pegmatites that cross-cut foliation in the meta-tonalites and supracrustal rocks (Nutman et al., 1997, 2002) are also inherited ages (±Pb-loss); (c) the Eoarchean Pb-Pb isochron ages found in BIF minerals and hydrothermal metasomatic minerals (Frei et al., 1999; Frei & Rosing, 2001) are associated with a metamorphic episode that is prior or related to the emplacement of the tonalites, (d) the ∼3,410 Sm-Nd isochron age of an undeformed Ameralik dike in Area A cannot be used to constrain the minimum deformation timing of the major tectonometamorphic event affected the ISB and deformed Ameralik dikes; and (e) the ∼3,600 Ma titanite ages obtained from Area A (where the Ameralik dikes are most undeformed; Crowley et al., 2002) represent crystallization and/or cooling, prior to the Neoarchean event, in a (largely) unstrained portion of the upper plate of the Neoarchean deformation event.

In addition to the disagreement over the tectonic evolution of the ISB, Nutman et al. (2022) argue that ISB supracrustal rocks contain evidence of significant strain contrasts including low strain zones. Such strain contrast, if at the scale of 10–1,000 m, would be consistent with thrust tectonics associated with plate tectonics in the Eoarchean (e.g., Appel et al., 1998; Nutman et al., 2002). However, in our prior work, no compelling evidence for such zones at that scale was observed (Webb et al., 2020; Zuo et al., 2021a). Nutman et al. (2022) argue that such strain contrasts can be observed in a chert/BIF unit, as an example. Specifically, they show a rootless fold in the unit (their Figure 2d) as an illustration of regionally dominant high strain, and they show a transition from a "low strain lithon" characterized by thicker quartz-magnetite bands relative to thinner bands of the "high strain zone" in the unit (their Figure 2e) as evidence for local preservation of low strain. However, this transition may represent a fold pattern that resulted from crystal-plastic deformation of rheologically similar layers within a ductile shear zone, that is, passive folding (e.g., Ez, 2000; Fossen, 2010). Such patterns can be commonly found in similar folds, sheath folds (Alsop & Holdsworth, 2006, 2012; Ez, 2000), and in the folded Isua supracrustal rocks (Figure 2; Figures DR2F and DR2H of Webb et al., 2020), and do not necessarily reflect a significant difference in strain.

Finally, Nutman et al. (2022) note that the dunites of the western arm of the ISB have B-type olivine crystallographic preferred orientations (CPO), which they interpret as having formed in an Eoarchean mantle wedge (following their work in Kaczmarek et al., 2016). However, as discussed in Waterton et al. (2022) and Zuo et al. (2021; preprint) a B-type olivine CPO pattern is not exclusive to mantle wedge conditions (e.g., Nagaya et al., 2014; Yao et al., 2019).

3. Metamorphic Record of Isua and Associated Areas

Nutman et al. (2022) critique our approach to metamorphic timing interpretations. Ramírez-Salazar et al. (2021) interpreted age compilation shows early and late Archean metamorphic ages. However, our compilation, as noted in the comment by Nutman et al. (2022), fell somewhat short as some young (∼2,520 Ma) ages were missed, in contrast to their compilation in Gauthiez-Putallaz et al. (2020) and Nutman et al. (2022). Nevertheless, our interpretation does not disagree with that of Gauthiez-Putallaz et al. (2020) regarding timing and conditions of late garnet overgrowth. Blichert-Toft and Frei (2001) have reported the only Lu-Hf and Sm-Nd garnets ages from post-tectonic grains within the ISB. Whereas their preferred interpretation of the data is a corrected 3,714 ± 24 Ma Sm-Nd crystallization age, it is noteworthy that both systems returned ∼2,800 Ma isochrons. Moreover, in the literature, timing of post-tectonic garnet is typically constrained with other minerals/whole rock data that show a wide range of time estimates (cf. Figure 2 in Ramírez-Salazar et al., 2021, and Figure 11 in Gauthiez-Putallaz et al., 2020). Given that we have not yet obtained any geochronological data for our samples, we followed a conservative approach and interpreted post-tectonic metamorphism to have likely occurred in the Neoarchean. Most importantly with respect to Nutman et al.'s (2022) comment, we emphasize that our interpretation does not dismiss garnet growth at ∼2.7 Ga. Furthermore, we agree with Gauthiez-Putallaz et al. (2020) regarding the relative timing of garnet rim growth with respect to the major deformation event: these rims grew statically over the pervasive foliation.

3.1. Re-Examination of Proposed Low T/P Records

Nutman et al. (2020, 2022) highlights the importance of low T/P gradients (200–500°C/GPa) for the interpretation of Isua suggesting low T/P gradients as unique features of plate tectonics. However, low T/P gradients are expected for both hypothesis (a) and (b) as in the heat-pipe scenario a low T/P gradient is equally predicted

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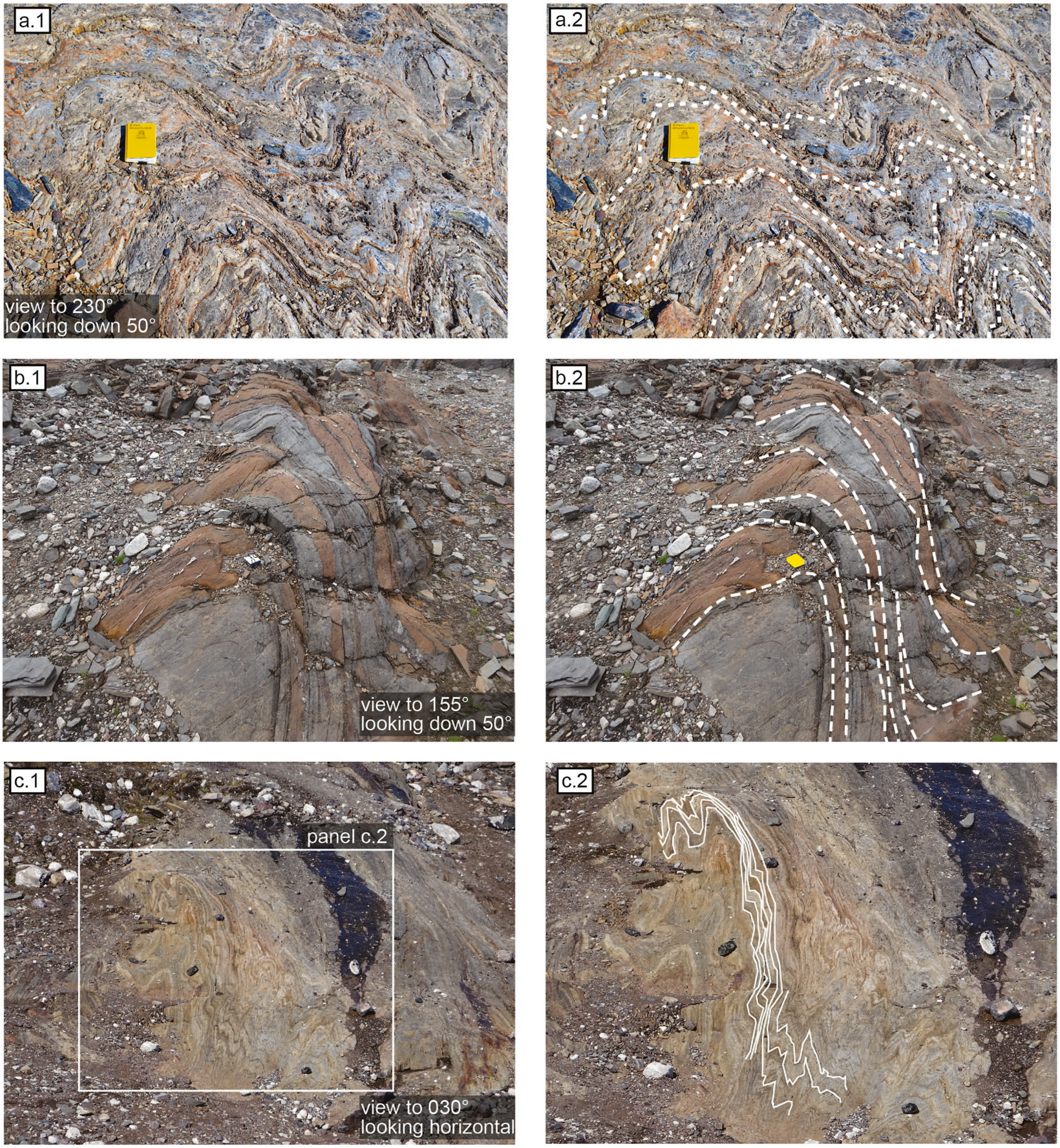

Figure 2. Deformed Isua supracrustal rock units showing sheath and curtain fold patterns with significant thickness changes (highlighted by white lines) of many folded layers. The layer thickness changes represent a fold pattern that resulted from crystal-plastic deformation of rheologically similar layers in a ductile shear zone, and is compatible with a bulk high strain (e.g., Ez, 2000; Fossen, 2010 [specifically Figure 11.24]; cf. Nutman et al., 2022). Field notebook in panel a and compass in panel b are for scale. The field of view of c.1 is about 15 m.

(Moore & Webb, 2013). We acknowledge, however, open discussions regarding the PT conditions within Isua region, particularly with regard to the interpretation of (a) Ti-humite bearing ultramafic rocks in the ISB, (b) a garnet-clinopyroxene bearing enclave in the 3.7 Ga tonalite, and (c) 3.7–3.8 Ga tonalites in the ISB (e.g., Nutman et al., 2020, 2022). While we agree that additional work to pinpoint the metamorphic evolution of the ISB through

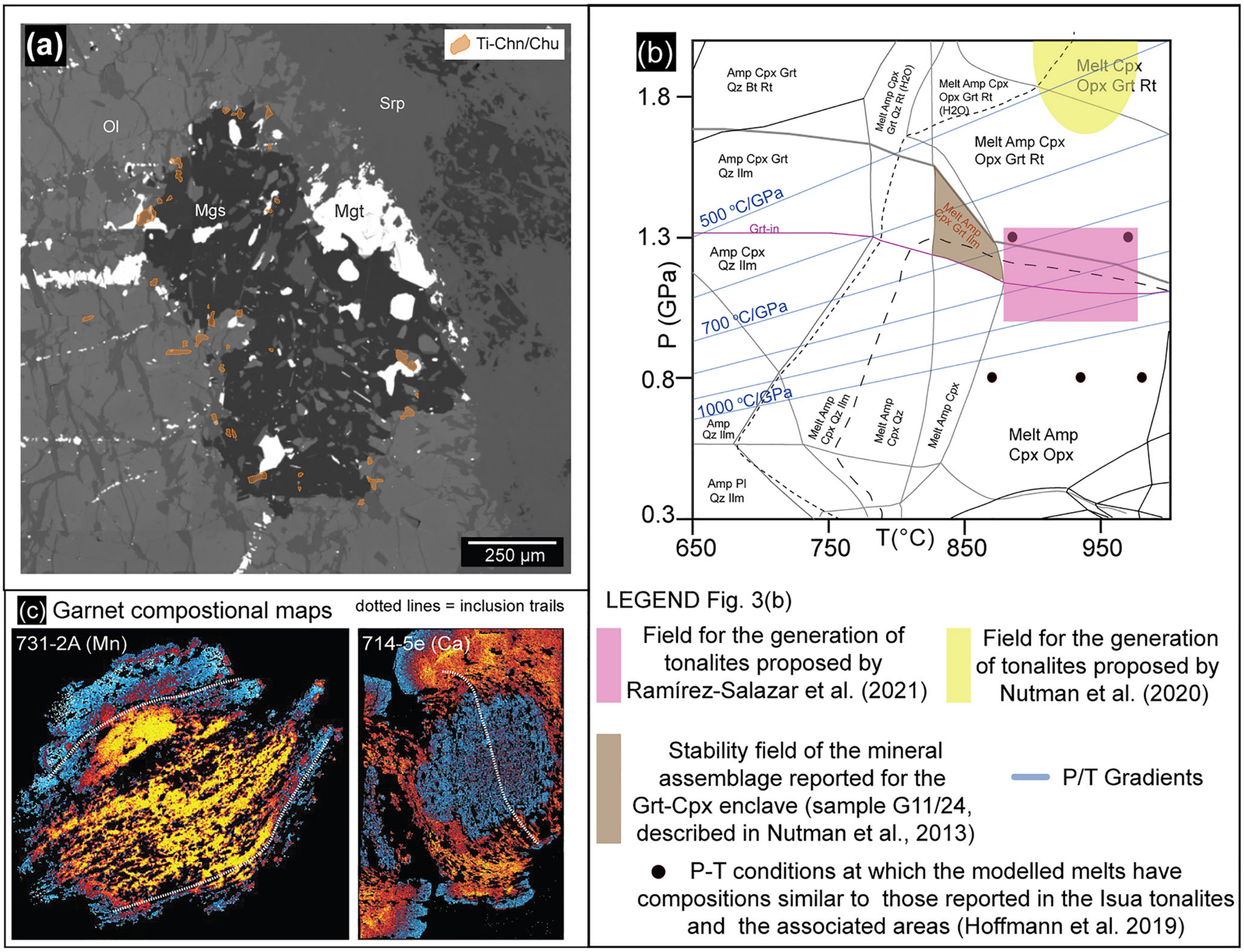

Figure 3. (a) Olivine breakdown reaction texture with the association of magnesite and Ti-clinohumite/Ti-chondrodite in Isua dunites (b) Phase diagram calculated with a representative enriched basalt composition (Hoffmann et al., 2019); interpreted stability fields for the generation of tonalites and stability field for the mineral assemblage of Grt-Px enclave (G11/24) are shown. (c) Compositional maps for garnets in meta-mafic (left) and metapelitic (right) rocks where inclusion trails continue through different compositional zones. Mineral abbreviations after Whitney and Evans (2010).

time would be helpful in testing the three hypotheses discussed for Isua, we note that the presence of low T/P gradients remains inconclusive in terms of the validity of the two hypotheses (1&2) discussed. Thus, we restrict our discussion here to some main points.

We agree with Nutman et al. (2022) that the origin of the metamorphic mineral assemblages reported in the ultramafic rocks of the ISB, and the interpretation that they are products of ultra-high pressure (UHP) metamorphism, are minimally addressed in Ramírez-Salazar et al. (2021). An extensive discussion was beyond the scope of the original paper. Nutman et al. (2022) stated that our argument, which involves impure carbonates, represents a chemical inadequate system; they favor the use of the experimental petrology framework from Shen et al. (2015), although the Ti-bearing serpentinized wehrlite and harzburgite compositions used in the experiments are equally not representing the ISB dunite compositions. Most importantly, we note that textural inspection of Isua dunite sample AW17724-2C reveals clear evidence of an olivine breakdown reaction to form antigorite + magnesite + Fe-oxide (Figure 3a). The presence of carbonates instead of brucite highlights the role of CO_2 to accurately describe phase relations for dunites in the ISB. Omitting CO_2 as a thermodynamic relevant component, as done by Nutman et al. (2020), has important consequences essentially questioning the extracted phase stabilities. Clearly, more work needs to be directed to resolve this disagreement.

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Nutman et al. (2013, 2020, 2022) used a partially melted garnet-clinopyroxene bearing enclave (sample G11/24) in the 3.7 Ga tonalite to propose high-pressure granulite facies metamorphism. The original interpretation by Nutman et al. (2020) suggested >1.3 GPa and 780°C (T/P ≈ 600°C/GPa), which Nutman et al. (2022) revised to lower pressure conditions (>0.9 GPa) (Figure 8 in Nutman et al., 2020; Figure 2 in Nutman et al., 2022). However, these P-T interpretations assume MORB bulk rock composition (Wyllie, 1977) that are not representative for the mafic ISB rocks or the Archean record in general (cf. Hoffmann et al., 2019). Alternative interpretations for the mineral assemblage of garnet-clinopyroxene enclave were already given by Ramírez-Salazar et al. (2021), suggesting higher gradients (≈700–800°C/GPa). Moreover, it has been reported that the mineralogy of G11/24 can be reproduced at upper-amphibolite facies condition in enriched tholeiites subjected to a high-influx of water (Pourteau et al., 2020). However, for a detailed P-T assessment the bulk rock chemistry of the enclave would be needed. Hence, none of these interpretations in definitive.

Nutman et al. (2020, 2022) argue that the chemistry of the tonalites in Isua and associated areas suggests melting under cold geothermal gradients (<500°C/GPa). As for the garnet-pyroxene enclave, Nutman et al. (2020) also based such interpretations on thermodynamic calculations of a MORB (Vielzeuf & Schmidt, 2001; Wyllie, 1977). However, it has already been discussed in the literature that melting of a typical MORB does not reproduce the geochemical characteristics of the Isua tonalites (cf. Hoffmann et al., 2019; Nagel et al., 2012). Instead, phase equilibria modeling of Hoffmann et al. (2019) (Figure 3b) calculated with enriched tholeiitic compositions convincingly showed that melts in equilibrium with garnet and rutile form at 1.3 GPa and 885°C–1020°C and melts in equilibrium with orthopyroxene-granulites that formed at 0.8 GPa and 870°C–980°C are predicted to have a similar major and trace element chemistry as observed in the natural tonalitic samples from the Eoarchean Itsaq Gneiss Complex of southwest Greenland. These conditions are substantially lower than the >1.5 GPa interpretation for the formation of the melts (Figure 3b) by Nutman et al. (2020, 2022). If true, the tonalites were most likely formed in P/T gradients of >700°C/GPa, rather than <500°C/GPa. At present, none of the analysis regarding tonalite petrogenesis is decisive; tonalite petrogenesis remains a highly debated topic. Recent works argue that "high-pressure" signatures can be explained without the necessity of deep melting (Pourteau et al., 2020; Smithies et al., 2019), while others suggest that a large portion of the TTGs were generated in cold deep gradients (Antonelli et al., 2021). The latter interpretation is typically associated with the operation of plate tectonics, specifically to convergent margins and subduction zones. However, cold gradients are equally predicted in the heat-pipe model (Moore & Webb, 2013). Thus, either TTG petrogenetic model is not exclusive to a plate tectonics scenario.

4. Garnet Zoning

Abrupt chemical changes within garnet porphyroblasts can be produced either by changes in fluid composition (Jamtveit & Hervig, 1994), changes in the garnet forming reactions (Spear et al., 1991), or as a consequence of different tectono-metamorphic events (Karabinos, 1984). Similarly, there are alternative explanations for changes in microstructural domains, such as element mobility in a heterogeneous matrix (Carlson et al., 2015; Dempster et al., 2017; Yang & Rivers, 2001). Hence, the various zoning patterns observed in garnet porphyroblasts of the ISB are not necessarily correlated to multiple tectono-metamorphic events. This has already been discussed in Section 4.1 of Ramírez-Salazar et al. (2021), where the continuity of inclusion trails across different core and annuli chemical zones is interpreted as product single metamorphic event that was followed by an overgrowth in a later, distinct event. This continuity of inclusion trails is a common observation for garnets porphyroblasts in the ISB (Figure 3c, and Figure 5 of Rollinson, 2003). However, we acknowledge that a more in-depth study (e.g., crystal lattice orientation, garnet growth analysis) should be conducted investigating the detailed microstructures of the Isua garnet porphyroblasts to reconcile the apparent contradictions in the interpretations presented by both groups.

5. Why Is There No Metamorphic Signature for ~3,800 and ~3,700 Ma Tonalite Crust Formation in the Heat-Pipe Setting?

Nutman et al. (2022) argue that the lack of high-grade metamorphism and TTG generation evidence in the ~3.8 Ga part of the ISB is inconsistent with the proposed heat-pipe evolution (Ramírez-Salazar et al., 2021; Webb et al., 2020; Zuo et al., 2021a). However, in the heat-pipe model (e.g., Figure 5 of Webb et al., 2020), the exposed ~3.7–3.8 Ga ISB would not have been the source of TTG. Instead, TTG would have been generated from partial melting of older and deeper hydrated mafic crust and then emplaced at higher crustal levels (Webb et al., 2020), so the ISB does not record high-grade metamorphism and metamorphic zircon growths associated with TTG generation. Therefore, observed metamorphic grades in the ISB are consistent with the proposed heat-pipe evolution (cf. Nutman et al., 2022).

6. Conclusions

The preservation status and formation timing of ISB's deformation and metamorphic features remains debatable. Based on currently available data, petrofabrics observed in the Isua supracrustal rocks can be viably interpreted as almost exclusively Eoarchean, a combination of Eoarchean deformation and Neoarchean overprints, or as only recording one major Neoarchean event, such that the Eoarchean tectonic settings of the ISB remain unresolved and the plate tectonic and heat-pipe models are both viable. Further work to refine constraints for the character and timing of deformation and metamorphism throughout Isua are necessary to distinguish between these three hypotheses. The central interpretative contribution of our works—that is, that non-plate tectonic hypotheses are viable for Eoarchean development of the ISB—remains robust, further constraints on the character and timing of deformation and metamorphism throughout Isua are necessary to distinguish unequivocally between the three hypotheses presented.

Data Availability Statement

No new data was used for this contribution.

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References

Alsop, G. I., & Holdsworth, R. (2006). Sheath folds as discriminators of bulk strain type. *Journal of Structural Geology*, *28*(9), 1588–1606. https://doi.org/10.1016/j.jsg.2006.05.005

Alsop, G. I., & Holdsworth, R. (2012). The three dimensional shape and localisation of deformation within multilayer sheath folds. *Journal of Structural Geology*, *44*, 110–128. https://doi.org/10.1016/j.jsg.2012.08.015

Antonelli, M. A., Kendrick, J., Yakymchuk, C., Guitreau, M., Mittal, T., & Moynier, F. (2021). Calcium isotope evidence for early Archaean carbonates and subduction of oceanic crust. *Nature Communications*, *12*(1), 2534. https://doi.org/10.1038/s41467-021-22748-2

Appel, P. W., Fedo, C. M., Moorbath, S., & Myers, J. S. (1998). Recognizable primary volcanic and sedimentary features in a low-strain domain of the highly deformed, oldest known (−3.7–3.8 Gyr) Greenstone Belt, Isua, West Greenland. *Terra Nova*, *10*(2), 57–62. https://doi.org/10.1046/j.1365-3121.1998.00162.x

Blichert-Toft, J., & Frei, R. (2001). Complex Sm-Nd and Lu-Hf isotope systematics in metamorphic garnets from the Isua supracrustal belt, West Greenland. *Geochimica et Cosmochimica Acta*, *65*(18), 3177–3189. https://doi.org/10.1016/S0016-7037(01)00680-9

Carlson, W. D., Hixon, J. D., Garber, J. M., & Bodnar, R. J. (2015). Controls on metamorphic equilibration: The importance of intergranular solubilities mediated by fluid composition. *Journal of Metamorphic Geology*, *33*(2), 123–146. https://doi.org/10.1111/jmg.12113

Crowley, J. (2003). U–Pb geochronology of 3810–3630 Ma granitoid rocks south of the Isua greenstone belt, southern West Greenland. *Precambrian Research*, *126*(3–4), 235–257. https://doi.org/10.1016/S0301-9268(03)00097-4

Crowley, J., Myers, J., & Dunning, G. (2002). Timing and nature of multiple 3700–3600 Ma tectonic events in intrusive rocks north of the Isua greenstone belt, southern West Greenland. *Geological Society of America Bulletin*, *114*(10), 1311–1325. https://doi.org/10.1130/0016-7606(2002)114<1311:TANOMM>2.0.CO;2

Dempster, T. J., Symon, S., & Chung, P. (2017). Intergranular diffusion rates from the analysis of garnet surfaces: Implications for metamorphic equilibration. *Journal of Metamorphic Geology*, *35*(6), 585–600. https://doi.org/10.1111/jmg.12247

Ez, V. (2000). When shearing is a cause of folding. *Earth-Science Reviews*, *51*(1–4), 155–172. https://doi.org/10.1016/S0012-8252(00)00020-9

Fossen, H. (2010). Extensional tectonics in the North Atlantic Caledonides: A regional view. *Geological Society, London, Special Publications*, *335*(1), 767–793. https://doi.org/10.1144/sp335.31

Frei, R., Bridgwater, D., Rosing, M., & Stecher, O. (1999). Controversial Pb-Pb and Sm-Nd isotope results in the early Archean Isua (West Greenland) oxide iron formation: Preservation of primary signatures versus secondary disturbances. *Geochimica Et Cosmochimica Acta*, *63*(3–4), 473–488. https://doi.org/10.1016/S0016-7037(98)00290-7

Frei, R., & Rosing, M. T. (2001). The least radiogenic terrestrial leads; implications for the early Archean crustal evolution and hydrothermal–metasomatic processes in the Isua supracrustal belt (West Greenland). *Earth and Planetary Science Letters*, *181*(1–4), 47–66. https://doi.org/10.1016/S0009-2541(01)00263-7

Friend, C. R., & Nutman, A. P. (2010). Eoarchean ophiolites? New evidence for the debate on the Isua supracrustal belt, southern West Greenland. *American Journal of Science*, *310*(9), 826–861. https://doi.org/10.2475/09.2010.04

Furnes, H., de Wit, M., Staudigel, H., Rosing, M., & Muehlenbachs, K. (2007). A vestige of Earth's oldest ophiolite. *Science*, *315*(5819), 1704–1707. https://doi.org/10.1126/science.1139170

Gauthiez-Putallaz, L., Nutman, A., Bennett, V., & Rubatto, D. (2020). Origins of high δ18O in 3.7–3.6 Ga crust: A zircon and garnet record in Isua clastic metasedimentary rocks. *Chemical Geology*. 119474. https://doi.org/10.1016/J.CHEMGEO

Gruau, G., Rosing, M., Bridgwater, D., & Gill, R. (1996). Resetting of Sm Nd systematics during metamorphism of >3.7-Ga rocks: Implications for isotopic models of early Earth differentiation. *Chemical Geology*, *133*(1–4), 225–240. https://doi.org/10.1016/s0009-2541(96)00092-7

Hoffmann, J. E., Zhang, C., Moyen, J.-F., & Nagel, T. J. (2019). The formation of tonalites–Trondjhemite–Granodiorites in early continental crust, Earth's oldest rocks. 133–168, https://doi.org/10.1016/b978-0-444-63901-1.00007-1

19449194, 2022, 5, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021TC007148 by Test, Wiley Online Library on [22/03/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

James, P. R. (1976). Deformation of the Isua block, West Greenland: A remnant of the earliest stable continental crust. *Canadian Journal of Earth Sciences*, *13*(6), 816–823. https://doi.org/10.1139/e76-084

Jamtveit, B., & Hervig, R. L. (1994). Constraints on transport and kinetics in hydrothermal systems from zoned garnet crystals. *Science*, *263*(5146), 505–508. https://doi.org/10.1126/science.263.5146.505

Kaczmarek, M. A., Reddy, S. M., Nutman, A. P., Friend, C. R. L., & Bennett, V. C. (2016). Earth's oldest mantle fabrics indicate Eoarchaean subduction. *Nature Communications*, *7*(1), 10665. https://doi.org/10.1038/ncomms10665

Karabinos, P. (1984). Polymetamorphic Garnet zoning from Southeastern Vermont. *American Journal of Science*, *284*(9), 1008–1025. https://doi.org/10.2475/ajs.284.9.1008

Moore, W. B., & Webb, A. A. G. (2013). Heat-pipe Earth. *Nature*, *501*(7468), 501–505. https://doi.org/10.1038/nature12473

Nagaya, T., Wallis, S. R., Kobayashi, H., Michibayashi, K., Mizukami, T., Seto, Y., et al. (2014). Dehydration breakdown of antigorite and the formation of B-type olivine CPO. *Earth and Planetary Science Letters*, *387*, 67–76. https://doi.org/10.1016/j.epsl.2013.11.025

Nagel, T. J., Hoffmann, J. E., & Münker, C. (2012). Generation of Eoarchean tonalite-trondhjemite-granodiorite series from thickened mafi c arc crust. *Geology*, *40*(4), 375–378. https://doi.org/10.1130/G32729.1

Nielsen, S. G., Baker, J. A., & Krogstad, E. J. (2002). Petrogenesis of an early Archaean (3.4 Ga) norite dyke, Isua, west Greenland: Evidence for early Archaean crustal recycling?*Precambrian Research*, *118*(1–2), 133–148. https://doi.org/10.1016/s0301-9268(02)00108-0

Nutman, A., Hagiya, H., & Maruyama, S. (1995). SHRIMP U-Pb single zircon geochronology of a Proterozoic mafic dyke, Isukasia, southern West Greenland. *Bulletin of the Geological Society of Denmark*, *42*(1), 17–22. https://doi.org/10.37570/bgsd-1995-42-02

Nutman, A. P. (1986). The early Archaean to Proterozoic history of the Isukasia area, southern West Greenland. *Bulletin—Gronlands Geologiske Undersogelse*, *154*, 1–80. https://doi.org/10.34194/bullggu.v154.6696

Nutman, A. P., Bennett, V. C., Friend, C. R., Yi, K., & Lee, S. R. (2015). Mesoarchaean collision of Kapisilik terrane 3070 Ma juvenile arc rocks and >3600 Ma Isukasia terrane continental crust (Greenland). *Precambrian Research*, *258*, 146–160. https://doi.org/10.1016/j.precamres.2014.12.013

Nutman, A. P., Bennett, V. C., Friend, C. R. L., Hidaka, H., Yi, K., Lee, S. R., & Kamiichi, T. (2013). The Itsaq Gneiss Complex of Greenland: Episodic 3900 to 3600 Ma Juvenile crust formation and recycling in the 3660 to 3600 Isukasian orogeny. *American Journal of Science*, *313*(9), 877–911. https://doi.org/10.2475/09.2013.03

Nutman, A. P., Bennett, V. C., Friend, C. R. L., & Rosing, M. T. (1997). ~3710 and ≥3790 Ma volcanic sequences in the Isua (Greenland) supracrustal belt; structural and Nd isotope implications. *Chemical Geology*, *141*(3–4), 271–287. https://doi.org/10.1016/s0009-2541(97)00084-3

Nutman, A. P., Bennett, V. C., Friend, C. R. L., & Yi, K. (2020). Eoarchean contrasting ultra-high-pressure to low-pressure metamorphisms (<250 to >1000°C/GPa) explained by tectonic plate convergence in deep time. *Precambrian Research*, *344*, 105770. https://doi.org/10.1016/j.precamres.2020.105770

Nutman, A. P., Bridgwater, D., Dimroth, E., Gill, R., & Rosing, M. (1983). Early (3700 Ma) Archaean rocks of the Isua supracrustal belt and adjacent gneisses. *Rapport Grønlands Geologiske Undersøgelse*, *112*, 5–22. https://doi.org/10.34194/rapggu.v112.7809

Nutman, A. P., & Collerson, K. D. (1991). Very early Archean crustal-accretion complexes preserved in the North Atlantic craton. *Geology*, *19*(8), 791–794. https://doi.org/10.1130/0091-7613(1991)019<0791:VEACAC>2.3.CO;2

Nutman, A. P., Friend, C. R., Bennett, V. C., & McGregor, V. R. (2004). Dating of the Ameralik dyke swarms of the Nuuk district, southern west Greenland: Mafic intrusion events starting from c. 3510 Ma. *Journal of the Geological Society*, *161*(3), 421–430. https://doi.org/10.1144/0016-764903-043

Nutman, A. P., Friend, C. R., & Hiess, J. (2010). Setting of the ~2560 Ma Qôrqut Granite complex in the Archean crustal evolution of southern west Greenland. *American Journal of Science*, *310*(9), 1081–1114. https://doi.org/10.2475/09.2010.12

Nutman, A. P., Friend, C. R., Horie, K., & Hidaka, H. (2007). The Itsaq Gneiss Complex of southern west Greenland and the construction of Eoarchaean crust at convergent plate boundaries. *Developments in Precambrian Geology*, *15*, 187–218. https://doi.org/10.1016/S0166-2635(07)15033-7

Nutman, A. P., & Friend, C. R. L. (2009). New 1:20,000 scale geological maps, synthesis and history of investigation of the Isua supracrustal belt and adjacent orthogneisses, southern west Greenland: A glimpse of Eoarchaean crust formation and orogeny. *Precambrian Research*, *172*(3–4), 189–211. https://doi.org/10.1016/j.precamres.2009.03.017

Nutman, A. P., Friend, C. R. L., & Bennett, V. C. (2002). Evidence for 3650–3600 Ma assembly of the northern end of the Itsaq Gneiss Complex, Greenland: Implication for early Archaean tectonics. *Tectonics*, *21*(1), 5-1–5-28. https://doi.org/10.1029/2000TC001203

Nutman, A. P., Friend, C. R. L., & Bennett, V. C. (2022) Comment: Zuo et al. (2021) and Ramírez-Salazar et al. (2021) Isua (Greenland) petrofabric and metamorphic studies do not indicate an Eoarchean 'heat-pipe' geodynamic regime. https://doi.org/10.1029/2021TC007036

Nutman, A. P., Friend, C. R. L., & Paxton, S. (2009). Detrital zircon sedimentary provenance ages for the Eoarchaean Isua supracrustal belt southern West Greenland: Juxtaposition of an imbricated ca. 3700 Ma juvenile arc against an older complex with 3920–3760 Ma components. *Precambrian Research*, *172*(3–4), 212–233. https://doi.org/10.1016/j.precamres.2009.03.019

Nyman, M. W. (1999). Fabric reactivation: An example from the Hualapai mountains, NW Arizona, USA. *Journal of Structural Geology*, *21*(3), 313–321. https://doi.org/10.1016/S0191-8141(99)00007-3

Pourteau, A., Doucet, L. S., Blereau, E. R., Volante, S., Johnson, T. E., Collins, W. J., et al. (2020). TTG generation by fluid-fluxed crustal melting: Direct evidence from the Proterozoic Georgetown Inlier, NE Australia. *Earth and Planetary Science Letters*, *550*, 116548. https://doi.org/10.1016/j.epsl.2020.116548

Ramírez-Salazar, A., Müller, T., Piazolo, S., Webb, A. A. G., Hauzenberger, C., Zuo, J., et al. (2021). Tectonics of the Isua Supracrustal belt 1: P-T-X-d constraints of a poly-metamorphic terrane. *Tectonics*, *40*(3). https://doi.org/10.1029/2020TC006516

Rollinson, H. (2002). The metamorphic history of the Isua Greenstone belt, west Greenland. *Geological Society—Special Publications*, *199*(1), 329–350. https://doi.org/10.1144/GSL.SP.2002.199.01.16

Rollinson, H. (2003). Metamorphic history suggested by garnet-growth chronologies in the Isua Greenstone belt, West Greenland. *Precambrian Research*, *126*(3–4), 181–196. https://doi.org/10.1016/S0301-9268(03)00094-9

Scott, L. (2019). *Dyke reactivation across the frictional-viscous transition: Precambrian deformation of Scourie dyke margins in NW Scotland*. Durham University.

Şengör, A., Lom, N., & Sağdıç, N. G. (2019). Tectonic inheritance, structure reactivation and lithospheric strength: The relevance of geological history. *Geological Society, London, Special Publications*, *470*(1), 105–136. https://doi.org/10.1144/sp470.8

Shen, T., Hermann, J., Zhang, L., Lü, Z., Padrón-Navarta, J. A., Xia, B., & Bader, T. (2015). UHP metamorphism documented in Ti-chondrodite- and Ti-clinohumite-bearing serpentinized ultramafic rocks from Chinese southwestern Tianshan. *Journal of Petrology*, *56*(7), 1425–1458. https://doi.org/10.1093/petrology/egv042

Smithies, R. H., Lu, Y., Johnson, T. E., Kirkland, C. L., Cassidy, K. F., Champion, D. C., et al. (2019). No evidence for high-pressure melting of Earth's crust in the Archean. *Nature Communications*, *10*, 1–12. https://doi.org/10.1038/s41467-019-13547-x

19449194, 2022, 5, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021TC007148 by Test, Wiley Online Library on [22/03/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

10.1029/2021TC007148

Spear, F. S., Kohn, M. J., Florence, F. P., & Menard, T. (1991). A model for garnet and plagioclase growth in pelitic schists: Implications for thermobarometry and P-T path determinations. *Journal of Metamorphic Geology*, *8*(6), 683–696. https://doi.org/10.1111/j.1525-1314.1990.tb00495.x

Vielzeuf, D., & Schmidt, M. W. (2001). Melting relations in hydrous systems revisited: Application to metapelites, metagraywackes and metabasalts. *Contributions to Mineralogy and Petrology*, *141*(3), 251–267. https://doi.org/10.1007/s004100100237

Webb, A. A. G., Müller, T., Zuo, J., Haproff, P. J., & Ramírez-Salazar, A. (2020). A non–plate tectonic model for the Eoarchean Isua supracrustal belt. *Lithosphere*, *12*(1), 166–179. https://doi.org/10.1130/l1130.1

White, R. V., Crowley, J. L., & Myers, J. S. (2000). Earth's oldest well-preserved mafic dyke swarms in the vicinity of the Isua greenstone belt, southern West Greenland. *Geology of Greenland Survey Bulletin*, *186*, 65–72. https://doi.org/10.34194/ggub.v186.5217

White, R. V., Crowley, J. L., Parrish, R., & David, K. (2000). Gate-crashing the billionth birthday party: Intrusion of dykes swarms in the Isua region. *EOS Transaction*, *81*, F1256.

Whitney, D. L., & Evans, B. W. (2010). Abbreviations for names of rock-forming minerals. *American Mineralogist*, *95*(1), 185–187. https://doi.org/10.2138/am.2010.3371

Wyllie, P. J. (1977). Crustal anatexis: An experimental review. *Tectonophysics*, *43*(1–2), 41–71. https://doi.org/10.1016/0040-1951(77)90005-1

Yang, P., & Rivers, T. (2001). Chromium and manganese zoning in pelitic garnet and kyanite: Spiral, overprint, and oscillatory (?) zoning patterns and the role of growth rate. *Journal of Metamorphic Geology*, *19*(4), 455–474. https://doi.org/10.1046/j.0263-4929.2001.00323.x

Yao, Z., Qin, K., Wang, Q., & Xue, S. (2019). Weak B-type olivine fabric induced by fast compaction of crystal mush in a crustal magma reservoir. *Journal of Geophysical Research: Solid Earth*, *124*(4), 3530–3556. https://doi.org/10.1029/2018JB016728

Zuo, J., Webb, A. A. G., Piazolo, S., Wang, Q., Müller, T., Ramírez-Salazar, A., & Haproff, P. J. (2021). Tectonics of the Isua Supracrustal belt 2: Microstructures reveal distributed Strain in the absence of major fault Structures. *Tectonics*, *40*(3), e2020TC006514. https://doi.org/10.1029/2020tc006514

19449194, 2022, 5, Downloaded from https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2021TC007148 by Test, Wiley Online Library on [22/03/2024]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License