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Proposal for a continent 'Itsquia' amalgamated at 3.66 Ga and rifted apart from 3.53 Ga: initiation of a Wilson Cycle near the start of the rock record

Abstract

A synthesis of the geological record of Earth's ten remaining oldest surviving gneiss complexes, each containing >3.6 Ga rocks, reveals a common history. We propose that the simplest scenario compatible with all observations is that of formation of an ancient continental mass, here named Itsquia, by 3.66 Ga from amalgamation of earlier quartzofeldspathic crust, followed by initiation of continental break-up at 3.53 Ga by rifting. Evidence for this is reconstructed from the remaining oldest rock record (only ca. 10,000 km² globally). Dominating the surviving fragments of the proposed Itsquia continent are 3.9 to 3.66 Ga tonalites that represent juvenile crustal additions with whole-rock initial $\epsilon_{\text{Nd}} > +1$ and zircon initial $\epsilon_{\text{Hf}} \approx 0$. Their trace element chemistry shows that they were derived by ca. 30 percent partial melting of garnetiferous, mostly eclogitized basic rocks, leaving behind a subcrustal garnet-rich restite. The tonalites contain inclusions of mafic rocks with chemical signatures diagnostic of mantle wedge fluxing, such as enrichment in the light rare earths and depletion of Nb and Ti. We interpret that this juvenile crust formed repeatedly in arc-like constructs at convergent plate boundaries. The Acasta Gneiss of Canada is the only undisputed surviving rock record of the proposed Itsquia continent where crust formation extends back to the Hadean. Before ca. 3.66 Ga, individual gneiss complexes show distinct chronologies of crust formation, yet despite their present-day isolation, they underwent identical 3.66 to 3.6 Ga high temperature orogenic events (Isukasian orogeny) - which we contend indicates that from 3.66 Ga these complexes had amalgamated into a single continental mass. Rare surviving 3.66 Ga high-pressure granulite rocks that underwent rapid decompression indicate tectonic crustal thickening then collapse during amalgamation. This was followed by almost 50 million years of high heat flow and lower pressure metamorphism, most probably in an extensional setting. Starting from ca. 3.53 Ga, we propose that komatiite and basalt eruption and dike emplacement marked the start of Itsquia's dismemberment by rifting. We further speculate that the deep mantle upwelling responsible for this plume-related magmatism was triggered by either the cascade of pre-3.66 Ga sub-Itsquia high density garnet-rich restitic subduction graveyards into the lower mantle or the thermal insulation effect of Itsquia. This resembles the mechanisms of supercontinent breakup throughout Earth's history. Hence we propose that Wilson Cycles of continent amalgamation and breakup were already initiated by the Eoarchean, near the start of the rock record. Australia's East Pilbara region was over the top of the plume, where the thermal impact destroyed Itsquia by melting to give rise to felsic igneous rocks coeval with komatiites. Greenland's Itsaq Gneiss Complex was peripheral to the plume, and hence was heavily diked at ca. 3.5 Ga, but was not melted.

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**PROPOSAL FOR A CONTINENT ‘ITSAQIA’ AMALGAMATED AT 3.66 Ga
AND RIFTED APART FROM 3.53 Ga: INITIATION OF A WILSON CYCLE
NEAR THE START OF THE ROCK RECORD**

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ABSTRACT. A synthesis of the geological record of Earth's ten remaining oldest surviving gneiss complexes, each containing >3.6 Ga rocks, reveals a common history. We propose that the simplest scenario compatible with all observations is that of formation of an ancient continental mass, here named *Itsaqia*, by 3.66 Ga from amalgamation of earlier quartzofeldspathic crust, followed by initiation of continental break-up at 3.53 Ga by rifting. Evidence for this is reconstructed from the remaining oldest rock record (only ca. 10,000 km² globally).

Dominating the surviving fragments of *Itsaqia* are 3.9-3.66 Ga tonalites that represent juvenile crustal additions with whole-rock initial $\epsilon_{\text{Nd}} > +1$ and zircon initial $\epsilon_{\text{Hf}} \approx 0$. Their trace element chemistry shows that they were derived by ca. 30% partial melting of garnetiferous, mostly eclogitized basic rocks, leaving behind a subcrustal garnet-rich restite. The tonalites contain inclusions of mafic rocks with chemical signatures diagnostic of mantle wedge fluxing, such as enrichment in the light rare earths and depletion of Nb and Ti. We interpret that this juvenile crust formed repeatedly in arc-like constructs at convergent plate boundaries. The Acasta Gneiss of Canada is the only undisputed surviving rock record of the proposed *Itsaqia* continent where crust formation extends back to the Hadean.

Before ca. 3.66 Ga, individual gneiss complexes show distinct chronologies of crust formation, yet despite their present-day isolation, they underwent identical 3.66-3.6 Ga high temperature orogenic events (*Isukasian orogeny*) – which we contend indicates that from 3.66 Ga these complexes had amalgamated into a single continental mass. Rare surviving 3.66 Ga high-pressure granulite rocks that underwent rapid decompression indicate tectonic crustal thickening then collapse during amalgamation. This was followed by almost 50 million years of high heat flow and lower pressure metamorphism, most probably in an extensional setting.

Starting from ca. 3.53 Ga, we propose that komatiite and basalt eruption and dike emplacement marked the start of *Itsaqia*'s dismemberment by rifting. We

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57
58 **Keywords:** Itsaqia, continent formation, mantle convection, plate tectonics,
59 Eoarchean, Wilson Cycle

INTRODUCTION

The Eoarchean (3.6-4.0 Ga) is the oldest part of the geological record in which diverse lithologies ranging from sedimentary rocks to mantle dunites are preserved, and has a known present-day extent on the order of 10,000 km² (for example, Nutman and others, 1996). Prior to that in the Hadean (>4.0 Ga), the record is restricted to small amounts (estimated to be <10 km²) of orthogneisses plus detrital and xenocrystic zircons in younger rocks (for example, Bowring and Williams, 1999; Froude and others, 1983).

Since the first discovery of Eoarchean rocks in West Greenland at the end of the 1960s (McGregor, 1968, 1973; Black and others, 1971), there have been other discoveries of these ancient materials scattered around the world (fig. 1). This paper presents the first synthesis of the worldwide record of Eoarchean rocks and then uses this information to produce a consistent model for early crustal evolution. We stress that it is necessarily at present a speculative model, which undoubtedly requires scrutiny and more data, but serves as a basis for discussion and future investigations. Our model is guided by the principle of Uniformitarianism - that there has been a continuum of evolving crust formation processes back to the start of the rock record (Talbot, 1973). This is combined with modern geochemical approaches (for example, Polat and Hofmann, 2003) and to a lesser degree structural appraisals (for example, Nutman and others, 2013) of these ancient crustal records. All observations show that there are striking similarities between the Eoarchean and the later geological record and it is therefore not mandatory to invoke exotic processes such as an Eoarchean crust predominantly molded by meteorite impacts. Most striking is the similarity between the oldest lithological record and the lithologies found at younger convergent plate boundaries (for example, Polat and Hofmann, 2003; Nutman and others, 2015). Thus we propose that near the beginning of the geological record in the Eoarchean, island-arc-like complexes (fig. 2) were swept together by convergent plate motions, leading to collisional orogeny at ~3.66 Ga, with the formation of a larger extent of 'continental' crust which we name here 'Itsaqia' (on the basis of the Itsaq Gneiss Complex terranes now comprising the largest extent of >3.6 Ga crust). Collisional

orogeny was followed by high temperature collapse and then extension with mafic intrusions, volcanism and dispersal of Itsaqia fragments. We contend that this represents initiation of a Wilson Cycle, near the start of the rock record.

THE EARLIEST ROCK RECORD

Preservation and Extent

With the exception of tiny amounts of late Hadean components in the Acasta Gneisses of Canada (Bowring and Williams, 1999; Iizuka and others, 2007), and possible, although currently disputed, small amounts of Hadean mafic crust in the Nuvvuagittuq Greenstone Belt (O'Neil et al, 2012) the oldest rock record is from the Eoarchean (4.0-3.6 Ga). Eoarchean rocks comprise about 1 millionth of Earth's surface, reflecting their small volume that survived >3.5 billion years of crustal recycling (Nutman and others, 1996). Nearly all are deformed and highly metamorphosed (550-850°C; fig. 3A) and occur as small fragments in gneiss complexes scattered across Greenland, southern Africa, Antarctica, Australia, Canada, China and Eastern Europe (fig. 1). The fragmented, small volume and poorly preserved nature of the Eoarchean geological record are major difficulties in establishing the processes giving rise to its rocks (Nutman and others, 2000; Nutman, 2006).

For all of the pre-3.6 Ga geological record, the Itsaq Gneiss Complex of southern West Greenland has by far the broadest range of lithologies and exposure (Table 1 in Nutman and others, 1996; Nutman, 2006), with some areas of epidote amphibolite facies metamorphism and low strain in which the protoliths are locally well preserved (Nutman and others, 1984a, 2007a; Komiya and others, 1999). Therefore the Itsaq Gneiss Complex's geological record is the most complete, and acts as a benchmark to compare and extend interpretation of the less well-preserved parts of the oldest rock record. Based on this overview of the oldest geological record, similarities in the histories of all the scattered Eoarchean crustal fragments (fig. 1) are detected, that leads us to present a scenario of >3.5 Ga crust formation in arc-like complexes (3.9-3.66 Ga), their convergence (ca. 3.66 Ga) with orogeny (Isukasian - 3.66-3.60 Ga)

and then dispersion via rifting marked by mafic dikes and bimodal volcanism (<3.53 Ga). This we regard as evidence for initiation of a Wilson Cycle near the start of the rock record.

The Itsaq Gneiss Complex, Greenland

This section briefly summarizes the geology and evolution of the Itsaq Gneiss Complex, based on the synthesis of Nutman and others (2013) and references cited therein. The Itsaq Gneiss Complex (dominated by rocks first known as the *Amîtsoq gneisses*) in the Nuuk region of southern West Greenland was the first body of Eoarchean rocks discovered (McGregor, 1968, 1973; Black and others, 1971). The complex is preserved over an area of ca. 3000 km² as tectonic slices within a Neoarchean orogen (Friend and others, 1988; Friend and Nutman, 2005a). Most of the complex was affected by 3.66-3.60 Ga high-grade metamorphism and ductile deformation causing widespread transformation of its protoliths into multi-component amphibolite-granulite facies gneisses (fig. 3A; Nutman and others, 1996; Friend and Nutman 2005b). Rare areas of lesser deformation show that these gneisses are derived from plutonic tonalite and younger crustally-derived granite (*sensu stricto*) protoliths (fig. 3B). The tonalites are 3.89 to 3.66 Ga old and the granites are 3.66 to 3.60 Ga old (fig. 1; Nutman and others, 1996; Hiess and others, 2009). The tonalites were produced by partial melting of eclogitized basic rocks, with either MORB or arc-like basalts proposed as potential source materials (Nutman and others, 1999; Hoffmann and others, 2011; Nagel and others, 2012). The production of these rocks involved melting of subducted or underthrust mafic crust, and would have left behind garnet-rich restite in the upper mantle. Given that these tonalites required ca. 30% melting of a mafic protolith (Nutman and others, 1999), the volume of restite would have been approximately double that of the tonalitic crust produced. The 3.66-3.6 Ga granites formed by partial melting of crust dominated by the tonalites (Baadsgaard and others, 1986; Hiess and others, 2011).

Volcanic and sedimentary rocks form <5% of the Itsaq Gneiss Complex and range in size from the 35-km long Isua supracrustal belt (Allaart 1976; Nutman and

Friend 2009 and references therein), down to sub-metre-sized enclaves (for example, McGregor and Mason 1977). Supracrustal sequences are dominated by amphibolites of island arc tholeiite and picrite geochemical affinity, with lesser amounts of quartz-magnetite banded iron formations, metacherts, marbles, and some felsic schists and metapelites of volcano-sedimentary origin (for example, Nutman and others, 1996; Polat and Hoffman, 2003; Bohlar and others, 2004, 2005; Friend and others, 2007; Jenner and others, 2008). These volcanic rocks are interpreted as the products of the earliest stage of Eoarchean arc-like assemblages, when partial melting was dominated by fluid fluxing of the mantle, prior to slab melting taking over as the dominant crust-forming mechanism to produce tonalites (fig. 2A,B; Nutman and others, 2013). Bodies of layered peridotites, with metagabbro locally grading into anorthosite, are fragments of differentiated intrusions (Nutman and others, 1996; Friend and others, 2002). More magnesian, very low Al, Ti and Ca ultramafic rocks are upper mantle tectonic slices intercalated with volcanic rocks (Nutman and others, 1996; Friend and others, 2002; Friend and Nutman 2011).

The Eoarchean tectonothermal evolution of the Itsaq Gneiss Complex can be divided into pre- and post-3.66 Ga phases (figs. 1 and 2). Prior to 3.66 Ga, record of high-grade metamorphism via low (<0.05) Th/U overgrowths on zircons is scarce (fig. 4). This is indicative of modest temperatures (generally $<500^{\circ}\text{C}$) following crust formation via tonalite emplacement. However, slices of upper mantle dunite and harzburgite were tectonically intercalated with volcanic and sedimentary rocks, prior to the emplacement of tonalites, indicative of >3.66 Ga tectonic activity *during* the formation of crust (Friend and others, 2002; Nutman and Friend, 2009).

After 3.66 Ga, there was a dramatic shift to crustal recycling by partial melting to produce crustally-derived sheeted granite complexes that were emplaced from the lower to middle crust (Nutman and others, 2013 and references therein), with widespread growth of low Th/U (<0.1) metamorphic zircon in restitic portions, coeval with high Th/U zircon in anatectic melt patches and granites *sensu stricto*. At deep crustal levels this was concomitant with syn-kinematic upper amphibolite to granulite facies metamorphism (Nutman and others, 1996; Friend and Nutman, 2005b).

181 Structural evidence suggests extensional deformation was important in the period
182 3.66-3.60 Ga (Nutman and others, 2013). At mid-crustal levels this is illustrated by
183 the extensional syn-magmatic fabric in restite schlieren within 3.645 Ga granite north
184 of the Isua supracrustal belt (fig. 5).

185 Extremely rare Eoarchean high-pressure granulite facies rocks have been
186 found in the Isua area (Nutman and others, 2013). These consist of 3.658 Ga
187 trondhjemitic melt patches formed in equilibrium with garnet and clinopyroxene (fig.
188 6). Using likely Isua basic rock starting compositions, thermodynamic calculation of
189 residual assemblages indicates garnet stable with melt at 10-14 kbar (Nagel and others,
190 2012). This shows that the switchover in tectonothermal styles at 3.66 Ga was marked
191 by tectonic crustal thickening, pointing to a collision between two bodies of buoyant
192 crust.

193 The Itsaq Gneiss Complex is cut by the Ameralik dykes (McGregor, 1973) as
194 several swarms emplaced 3.515-3.500 Ga (Nutman and others, 1996, 2004). They
195 have tholeiitic and noritic compositions (the latter probably reflecting crustal
196 contamination of komatiite magma). Deep crustal (not Isua area) Itsaq Gneiss
197 Complex host rocks to the dikes record this event by the sporadic growth of
198 metamorphic zircon of this age (fig. 4). Because of superimposed strain, the Ameralik
199 dykes are now preserved in most places as sub-concordant strips of amphibolite in
200 their host gneisses. The emplacement of the Ameralik dykes reflects the breakup and
201 dispersion of an Eoarchean continental mass larger than the preserved Itsaq Gneiss
202 Complex (Nutman and others, 2004).

203 204 West of Scoresbysund, East Greenland

205 The Paleozoic Caledonian orogen of East Greenland contains slices of
206 Laurentian Precambrian basement intercalated with Paleozoic cover sequences (for
207 example, Leslie and Higgins, 2008). In the southern part of the orogen, the Niggli
208 Spids thrust sheet west of Scoresbysund contains an Archean gneiss complex (Steiger
209 and others, 1979). Recent more detailed field studies, integrated with U-Pb zircon
210 dating, have shown that the complex contains ca. 3.61 and 3.07-2.98 Ga tonalitic

gneisses, which underwent metamorphism and intrusion of granites between 2.79 and 2.68 Ga (Johnston and Kylander-Clark, 2013). Magmatic zircons from the 3.61 Ga tonalites have a juvenile initial ϵ_{Hf} value of ca. 0, whereas those of the youngest granite have an ϵ_{Hf} value of ca. -16, indicative of recycling of juvenile Eoarchean crust (Johnston and Kylander-Clark, 2013). Presently, there have been no reports of supracrustal or mafic rocks with these gneisses, and due to the reconnaissance nature of work in this remote area, the extent of the Eoarchean component is not known.

The Uivak Gneisses, Labrador, Canada

The Uivak gneisses of Labrador, face Greenland's Itsaq Gneiss Complex across the Davis Strait, and were the second discovery of Eoarchean rocks (Hurst and others, 1975). Many of the Labrador Eoarchean rocks are strongly affected by Neoarchean granulite facies metamorphism with anatexis (Collerson and others, 1982), which destroyed most of the record of Eoarchean processes. The coastal region between the Saglek and Hebron fiords has been the focus of studies because the Eoarchean rocks here escaped Neoarchean migmatization. The Uivak Gneisses are dominated by a suite of migmatitic tonalitic-granitic orthogneisses (Uivak 1). Integrated field studies and zircon geochronology indicates that these contain ca. 3.73 Ga juvenile tonalitic rocks, 3.65-3.60 Ga neosome components and also ca. 3.86 Ga xenocrysts (Collerson, 1983; Schiøtte and others, 1989a; Shimojo and others, 2012). The Uivak 1 tonalitic protoliths contain inclusions of the Nulliak assemblage, a suite of metavolcanic, sedimentary, gabbroic and ultramafic rocks (Nutman and others, 1989), from which a felsic volcano-sedimentary unit has yielded a U-Pb zircon age of ca. 3.73 Ga (Schiøtte and others, 1989b). The Nanok gneisses in outer Hebron fiord have a maximum protolith age of 3.91 Ga (Shimojo and others, 2012), thus must be the basement of, or be tectonically intercalated with, Nulliak supracrustal rocks formed at 3.73 Ga. The Uivak 2 gneisses are a suite of porphyritic quartz monzonite and ferrodiorite intruded into the Uivak 1 suite and its Nulliak assemblage of supracrustal rocks. All these rocks are cut by the Saglek dikes, which are correlated with the Ameralik dykes in Greenland.

The Narryer Gneiss Complex, Western Australia

The Narryer Gneiss Complex is dominated by complex migmatites with a preponderance of granitic components (Myers, 1988; Kinny and Nutman, 1996). Zircon geochronology of the Meeberrie gneisses (for example, figure 2 of Kinny and Nutman, 1996) on the eastern side of the complex indicates that several generations of 3.66-3.60 Ga igneous zircons are present, which carry inherited older magmatic cores with ages up to ca. 3.73 Ga (Kinny and Nutman, 1996). Small amounts of preserved 3.73 Ga tonalites have been found south of the Jack Hills, and have positive whole-rock initial ϵ_{Nd} values of +1.7 and +1.8 (Nutman and others, 1991, 1993b). Dismembered fragments of gabbro, ultramafic rocks and anorthosite known as the Manfred Complex are scattered through the Narryer Gneiss Complex (Myers, 1988), from which an anorthosite yielded 3.73 Ga magmatic zircons (Kinny and others, 1988). The tonalites and gabbroic inclusions are interpreted as surviving vestiges of juvenile crust within a 'sea' of migmatites produced by elevated crustal temperature between ca. 3.66 and 3.6 Ga (Kinny and Nutman, 1996). The migmatites dominated by 3.66-3.60 Ga igneous components have T_{DM} model ages <3.8 Ga, hence they formed from recycling of Eoarchean, not Hadean, juvenile crust (Nutman and others, 1993). The Narryer Gneiss Complex experienced Paleoproterozoic thermal events, with its western flank containing the 3.46-3.42 Ga Eurada gneisses (Nutman and others, 1991) and porphyritic granitoids were emplaced in the east at ca. 3.3 Ga (Kinny and others, 1990). In the Neoproterozoic and Paleoproterozoic, the Narryer Gneiss Complex experienced further deformation and metamorphism, and was juxtaposed with the sedimentary rocks of Mount Narryer and the Jack Hills, with their inventory of Hadean and younger zircons (for example, Froude and others, 1983; Compston and Pidgeon, 1986; Wilde and Spaggiari, 2007).

Mount Sones and Adjacent Nunataks, Antarctica

Mount Sones and the adjacent nunataks lie in the Napier Complex, and contain complex, migmatitic upper amphibolite to granulite facies orthogneisses (Harley and

Kelly, 2007). The orthogneisses present robust U-Pb zircon evidence for the presence of Eoarchean crust. Black and others (1986) suggested a likely protolith age of 3.927 Ga for a tonalitic orthogneiss. The Eoarchean protolith zircons were strongly affected by a Neoarchean thermal event, which promoted both the growth of new zircon but also the redistribution of radiogenic Pb, in some cases giving reverse discordant U-Pb ages with ≥ 4 Ga apparent $^{207}\text{Pb}/^{206}\text{Pb}$ ages, due to unsupported radiogenic Pb (Williams and others, 1984; Kusiak and others, 2013). Reassessment of these data with current data reduction and assessment techniques suggest a protolith age of 3844 ± 81 Ma (Harley and Kelly, 2007). Other Mount Sones orthogneisses studied in less detail have yielded ca. 3.8 Ga protolith ages, with the same evidence of Neoarchean thermal overprint (Harley and Kelly, 2007). Thus an orthogneiss from Gage Ridge, ca. 40 km from Mount Sones also yielded an Eoarchean age (Harley and Black, 1997). Reassessment of the data indicates an age of 3840^{+30}_{-20} Ma, within error of the Mount Sones sample. Presently, there is no geochronological evidence for Eoarchean supracrustal rocks in the Napier Complex.

The Acasta Gneisses, Northwest Territories, Canada

The Acasta Gneisses are a diverse assemblage of amphibolite facies migmatites of $<100 \text{ km}^2$ extent at the western edge of the Slave Province, Canada (Bowring and others, 1989). They contain the world's oldest rocks, with ages between 4.03 and 3.96 Ga (Bowring and others, 1989; Stern and Bleeker, 1998; Bowring and Williams, 1999; Iizuka and others, 2007). However, these Hadean rocks are a volumetrically minor part of the Acasta Gneisses. More voluminous are 3.74-3.72 Ga tonalites and diorites and granites with ages between 3.66 and 3.58 Ga (see summary by Iizuka and others, 2007). Zircon xenocrysts are common in the younger granitic components of the Acasta Gneisses. Most of these are Eoarchean in age, but Iizuka and others (2006) detected a 4.2 Ga xenocryst. Hf chondritic model ages for Acasta Gneiss zircons range between ca. 3.75 Ga up to >4.2 Ga (Iizuka and others, 2009). The younger model ages are in accord with the presence of predominantly Eoarchean rocks, whereas the older >4.2 Ga model ages are in accord with the 4.2 Ga zircon xenocryst,

demonstrating the presence of a pre-4.03 Ga Hadean crustal component in the Acasta Gneisses. The Acasta Gneisses contain hornblendic mafic inclusions, for which protolith ages have not yet been established. The Acasta Gneisses are intruded by 3.36 Ga granites, accompanied by metamorphism and anatexis (Bleeker and Stern, 1997), followed by emplacement of several generations of Neoarchean granites.

Anshan Area, Northeastern China

The Archean North China Craton is dominated by 2.55-2.49 Ga plutonic rocks of diverse origins with associated volcanic and sedimentary rocks, including major bodies of banded iron formation (Nutman and others, 2011; Zhai and Santosh, 2011 and references therein). At Anshan city in Liaoning Province Eoarchean rocks have been identified at three localities – Beijiafen, Dongshan and Shengousi (Song and others, 1996; Liu and others, 2007; Wan and others, 2012). The Anshan Eoarchean rock occurrences are all small, with a total areal extent of $<5 \text{ km}^2$. At Beijiafen they are juxtaposed with ca. 3.36 Ga supracrustal rocks (Song and others, 1996). The Eoarchean rocks form enclaves within, and are intruded by, younger Archean granitoids - now orthogneisses and metagranitoids; ca. 3.45 Ga trondhjemitites at Shengousi, ca. 3.3 Ga Chentaigou granite, ca. 3.14 Ga Lishan trondhjemitite, 3000 Ma Dong'anshan granite, 3000-2900 Ma Tiejiashan potassium-rich granite and the ca. 2.5 Ga Qidashan granite. The Beijiafen gneisses are the oldest, with an age of ca. 3.81 Ga, and are fine-grained, layered rocks of trondhjemitic composition (Liu and others, 1992, 2007; Song and others, 1996). Quartz diorites at Dongshan are locally little-deformed, and clearly have plutonic protoliths, with an age of 3.79 Ga (Wan and others, 2005). At Shengousi, strongly deformed trondhjemitic gneisses have a protolith age of 3.77 Ga (Wan and others, 2012). At the three occurrences, there is variable thermal overprint between 3.65-3.6 Ga, marked by some zircon recrystallisation/regrowth and probably the intrusion of pegmatites (Liu and others, 2007; Wan and others, 2012). Wu and others (2008) reported a ca. 3.88 Ga zircon xenocryst from a 3.3 Ga Chentaigou granite gneiss. Currently, this is the oldest crustal component at Anshan. Whole-rock Nd and zircon Hf isotopic studies demonstrate that

the Anshan Eoarchean rocks are juvenile, and not recycled Hadean crust (Song and others, 1996; Wu and others, 2005, 2008).

Ancient Gneiss Complex, Southern Africa

The term Ancient Gneiss Complex was introduced to embrace several lithologically distinct early Archean units in central Swaziland (Hunter and others, 1978). The Complex is a typical Archean basement terrain comprising metagranitoids and multiply deformed orthogneisses of mainly tonalitic composition (Kröner, 2007 and references therein). These contain remnants of supracrustal rocks, known collectively as the Dwalile Supracrustal Suite, which consists of mostly mafic rocks, with felsic (volcano-sedimentary?) gneisses and BIF. The Ngwane Gneiss (Wilson, 1982) is the oldest part of the Complex, and contains components of different age, even down to the single outcrop scale. Kröner and others (1989) demonstrated the presence of 3.644 Ga components as the oldest, with younger components at 3.56, 3.51, 3.45 and 3.17 Ga. On the other hand, Dwalile metagreywackes yielded homogeneous zircon populations of ca. 3.55 Ga, suggesting that some of the orthogneisses are older than the supracrustal rocks (Kröner and Tegtmeyer, 1994). Ngwane gneiss and Dwalile suite supracrustal rocks have whole-rock initial ϵ_{Nd} values of ca. +1, indicating that they are predominantly juvenile additions to the crust in the late Eoarchean (Kröner and others, 1993). However, using a model of non-chondritic evolution of hafnium in the Eoarchean and Hadean mantle, Kröner and others (2014) suggested more ancient crust was recycled to form these granitoids.

Podolian and Azov Domains, Ukraine

The Ukrainian Shield is a large region of Archean and Paleoproterozoic crust in the East European Craton (Claesson and others, 2006 and references therein). Important crust formation occurred in the Meso- Neoproterozoic with the development of greenstone belts and TTG associations. Crustal extension in the Proterozoic led to the formation of banded iron formations and emplacement of ‘within plate’ plutonic suites. In the greenstone sequences there is evidence of Eoarchean crust in the form of

3.8-3.6 Ga detrital zircons (Bibikova and others, 2010). In the boundary between the Azov and Middle Dnepr Domains there are tonalitic gneisses with ages of ca. 3.65 Ga (Bibikova and Williams, 1990). In the Podolian Domain, some enderbitic gneisses are derived from 3.65 Ga granites, with older inherited ca. 3.75 Ga components. They were strongly reworked in a ca. 2.8 Ga tectonothermal event (Claesson and others, 2006).

Nuvvuagittuq, Québec, Canada

A small sliver of Eoarchean rocks, suggested by some workers to hold Hadean components, occurs at Nuvvuagittuq in the northeastern part of the Superior Province, Québec, Canada. There is a refolded, sheared, isocline of supracrustal rocks known as the Nuvvuagittuq supracrustal belt, which contains predominantly mafic amphibolite rocks with rare felsic schists, oxide-rich and quartz-rich iron formations, conglomeratic units, and metamorphosed gabbro and ultramafic layers (Dauphas and others, 2007; O'Neil and others, 2007, 2008; David and others, 2009). The belt is flanked by, and contains invaginations of, orthogneisses with zircon U-Pb ages of 3.66 and 3.82 Ga (David and others, 2009). Therefore there is no doubt that the area contains remnants of Eoarchean crust. From whole-rock Nd isotopic studies (David and others, 2009) these are juvenile crustal additions in the Eoarchean, and not recycled Hadean crust. However the age and significance of the Nuvvuagittuq supracrustal belt rocks is less straightforward. The focus for establishing their age has been on the 'faux amphibolites' - a group of heterogeneous, cummingtonite-rich (quartz + biotite + plagioclase + anthophyllite + garnet) amphibolitic gneisses favored to have formed in a suprasubduction zone setting (O'Neil and others, 2007, 2011). These resemble rocks that occur commonly in many Archean gneiss complexes and are interpreted as metamorphosed weathered volcanic lithologies. The faux amphibolites preserve lower $^{142}\text{Nd}/^{144}\text{Nd}$ ratios than the terrestrial standard ($\epsilon^{142}\text{Nd} = -0.07$ to -0.15) and produce a ^{146}Sm - ^{142}Nd isochron with an age of 4280^{+53}_{-81} Ma. These data have been interpreted as evidence that the rocks are Hadean (O'Neil and others, 2008). However, igneous cores of detrital zircons from Nuvvuagittuq supracrustal belt metasedimentary rocks (from

within the same supracrustal successions that preserve low $^{142}\text{Nd}/^{144}\text{Nd}$ define a maximum age of ca. 3.78 Ga (Cates and others, 2013). The zircon U-Pb ages and ^{143}Nd model age data thus suggest that the Hadean isochron may reflect the age of the source from which the rocks were originally derived and not the actual age of the rocks themselves. Furthermore, a conglomerate unit within the belt contains ca. 3.3 Ga high Th/U zircons (Cates and Mojzsis, 2007) that are possibly detrital grains derived from an igneous source. If this is the case, then at least part of the belt has an age of ≤ 3.3 Ga. Thus although there is robust evidence for Eoarchean orthogneisses in the Nuvvuagittuq area, the age of the Nuvvuagittuq supracrustal belt rocks is yet to be resolved (≤ 3.3 Ga to ca. 4.3 Ga?). As with other ancient supracrustal belts such as Isua (Nutman and Friend, 2009), it may transpire that packages of different age and origin are tectonically intercalated within the Nuvvuagittuq supracrustal belt.

The Jack Hills and Mount Narryer Eoarchean-Hadean Detrital Zircons, Western Australia

In the northeastern part of the Archean Yilgarn Craton of Western Australia, the Eoarchean Narryer Gneiss Complex contains tectonic intercalations of younger meta-sedimentary rocks, the largest of which occur at Mount Narryer and at the Jack Hills. Most of the detrital zircons in these units have ages of 3.75-3.3 Ga, with a minority of Hadean grains present (Froude and others, 1983; Compston and Pidgeon, 1986). The source rocks of the Hadean zircons have not been found, and the probability is very low that they are in the Narryer Gneiss Complex (Nutman and others, 1991). As the Jack Hills Hadean zircons are the largest inventory of surviving terrestrial Hadean material, they are an important resource to understand the earliest Earth. Therefore, they have been the focus of many studies, most of which have been on one sedimentary layer in the Jack Hills, which contains ca. 6% Hadean zircons. So far, about 200,000 zircons from this layer have been individually dated, in order to find the Hadean ones for further geochemical study (see Cavosie and others, 2007 and Bell and others, 2011 for summaries). The study of the Hadean zircons has led to divergent views concerning crust-forming processes in the Hadean, which are beyond the scope of this study. In the

context of this paper, three salient facts have arisen from Hf isotopic studies of these zircons (fig. 7). First, the Hadean zircons are derived from several pulses of juvenile crust, and they are not all produced by recycling of some ca. 4.35 Ga ‘primordial’ crust (Bell and others, 2011 and references therein). Secondly, the Eoarchean grains were derived from crust formed in the Eoarchean, *not* from further recycling Hadean crust (Bell and others, 2011 and references therein), with their source matching the Narryer Gneiss Complex rocks that are tectonically intercalated with the Jack Hills and Mount Narryer metasedimentary belts. Thirdly, the abundant 3.3 Ga detrital zircons were formed from recycling of Eoarchean crustal components, with seemingly *none* formed from Hadean sources (data in Bell and others, 2011). The implication of this is that the sources of the Jack Hills Hadean and Eoarchean zircons were not proximal to each other until *after* 3.3 Ga (fig. 7). This indicates that the marrying of these sources occurred in an assembly event much younger ($\ll$ 3.3 Ga) than the 3.66 Ga assembly events that gave rise to Itsaia. Therefore we contend that the Hadean zircons found in the Jack Hills and Mt Narryer sedimentary rocks were *never* part of the continent Itsaia, unlike the Eoarchean zircons in the same rocks (fig. 1)

Eoarchean Detrital Zircons in Paragneisses from the Beartooth Range, Montana, USA

In the Beartooth Mountains of Montana, USA, the ca. 2.8 Ga Long Lake magmatic complex contains tectonic slivers and enclaves of amphibolites, migmatites, metaquartzites, iron formations, and up to ca. 3.5 Ga old quartzofeldspathic gneisses (Henry and others, 1982; Mueller and others, 1998). The metaquartzites are usually found as discontinuous layers and boudins (mostly <10 m thick). They are thoroughly deformed, with no original contacts with adjacent lithologies preserved. These rocks have a detrital zircon population dominated by 3.4-3.3 Ga grains but with Eoarchean zircons constituting >10% of the population (Mueller and others, 1998). The degree of concordancy of the U-Pb ages, high Th/U values and magmatic-like REE signatures of these zircons suggest they are predominantly grains recycled from Eoarchean igneous rocks (Mueller and Wooden, 2012). The Hf isotopic signatures of the

Eoarchean grains show Bulk Silicate Earth model ages ranging from ca. 3.7 to ca. 4.1 Ga (fig. 7). In most cases the model ages are older than the grains, indicating their magmatic source regions formed largely by the remelting of early Eoarchean to late Hadean crust (Mueller and Wooden, 2012). This provides a link in provenance to the world's most ancient rocks preserved in the Acasta Gneisses, rather than other relicts of early crust, exemplified by the juvenile Eoarchean Itsaq Gneiss Complex.

Eoarchean Detrital Zircons in the North China Craton Caozhuang Quartzite, E. Hebei, China

In the Qian'an area of East Hebei province, 2.55-2.5 Ga arc-related rocks of the North China Craton contain enclaves and tectonic slices of pre-Neoproterozoic rocks (Liu and others, 1992, 2007; Wilde and others, 2008; Nutman and others, 2011). These are dominated by rafts of 3.2-2.9 Ga tonalitic to granitic orthogneisses (Nutman and others, 2011), but also include an assemblage of siliceous, locally fuchsite-bearing rocks, known as the Caozhuang quartzite (Liu and others, 1992). These rocks occur as slices and pods within strongly tectonized quartzofeldspathic schists and pegmatite. The Caozhuang quartzite contains zircons ranging in age from 3.88 to 3.54 Ga (Liu and others, 1992; Nutman and others, 2011). The quartzite is interpreted as a strongly tectonised sedimentary rock, that was deposited post-3.54 Ga. Hf isotopic studies of these zircons demonstrate that they are all derived from crust formed in the Eoarchean, without a detectable Hadean input (Wu and others, 2005).

DISCUSSION

Wilson Cycles

Neoproterozoic and Phanerozoic supercontinent formation, breakup, dispersion and re-amalgamation (for example, Rodinia and Pangea) are linked with cycles in Earth's convective regime, magmatic activity and variable degrees of thermal insulation by continental crust (for example, Piper, 1974; Hofmann and White, 1982; Hoffman, 1989). With the strong evidence for Paleoproterozoic amalgamation of the continent Columbia (Rogers and Santosh, 2002; Zhao and others, 2004) followed by its late

Paleoproterozoic – Mesoproterozoic dispersion and now also for the 3.2-3.0 Ga continent Vaalbara (Zegers and others, 1998) the evidence suggests that these Wilson Cycles are likely to have extended back beyond the Mesoarchean. How much farther back into time did these cycles extend?

From available published geologic, U-Pb zircon chronological and radiogenic isotope tracer data we have compiled Earth's 3.9-3.5 Ga crustal evolution (figs. 1 and 2), and propose that a Wilson Cycle is evident at near start of the rock record. We propose that a continent, named here *Itsaqia*, had formed by 3.66 Ga, and that from 3.53 Ga it was being rifted apart.

3.9-3.66 Ga; Formation of Juvenile Crust in Itsaqia

U-Pb zircon dating shows that the Itsaq Gneiss Complex contains several generations of tonalite suites, with ages from 3.89 to 3.66 Ga (Nutman and others, 1996, 2007b; Crowley and others, 2002; Hiess and others, 2009). Whole-rock Rb-Sr, Sm-Nd and zircon Lu-Hf isotopic studies (fig. 7; for example, Moorbath and others, 1972; Bennett and others, 1993, 2007; Hiess and others, 2009; Kemp and others, 2009) show that the tonalites dominating the Itsaq Gneiss Complex are juvenile crust. Whole-rock geochemical studies of non-migmatized tonalites indicates they are predominantly products of partial melting of eclogitized mafic rocks (Nutman and others, 1999; Hoffmann and others, 2011; Nagel and others, 2012), and the geochemical signatures of mafic and intermediate rocks associated with them indicate partial melting of upper mantle fluxed by fluids (Polat and Hofmann, 2003; Jenner and others, 2008). Therefore Itsaq Gneiss Complex crust is interpreted to have formed at convergent plate boundaries, in an environment analogous to Phanerozoic intra-oceanic arcs (figs 2 A,B; Dilek and Polat, 2008; Friend and Nutman 2010).

The lesser amount of detailed information from other Eoarchean gneiss occurrences is congruent with the Itsaq Gneiss Complex data, with the predominance of juvenile crust formed earlier in the Eoarchean (fig. 1). We contend that 3.9-3.66 Ga parts of Itsaqia largely formed as intra-oceanic arc assemblages. These occasionally amalgamated together, but, prior to 3.66 Ga, tectonic crustal thickening and thermal

511 impact within the crust were minimal. Concrete evidence for the lack of high thermal
512 impact in these pre-3.66 Ga events comes from the scarcity of >3.66 Ga low Th/U
513 (<0.1) metamorphic zircon and the lack of >3.66 Ga metamorphic structure
514 overgrowths on zircon grains (fig. 4). This suggests convergent plate boundary
515 processes in an open oceanic realm, unimpeded by collision with ‘continent’-sized
516 bodies of buoyant quartzofeldspathic crust. By ca. 3.66 Ga, juvenile arc assemblages
517 in Itsaia had expanded laterally, with the youngest examples perhaps represented by
518 the youngest ca. 3.66 Ga tonalites and quartz diorites in the Itsaia Gneiss Complex
519 (Bennett and Nutman, unpublished data).

520 3.66-3.60 Ga; the Isukasian Orogeny, a Pan-Itsaia Tectonothermal Event

521 All the disparate fragments of ancient crust that we contend belonged once to one
522 ancient continent at the end of the Eoarchean show evidence of ca. 3.66-3.6 Ga
523 tectonothermal history (fig. 1). Applying Occam’s Razor: *Entia Non Sunt*
524 *Multiplicanda Praeter Necessitatem* (entities are not to be multiplied without
525 necessity) we consider that until it is *proven* that the 3.66-3.6 Ga tectonothermal
526 activity observed in the Eoarchean crustal fragments was occurring in unconnected
527 orogens dispersed around the globe, this activity should be considered as expressions
528 of a single related event welding together one continental mass. The 3.66-3.6 Ga
529 tectonothermal event is named the *Isukasian orogeny* (Nutman and others, 2013),
530 after the geographic region at the northern end of the Itsaia Gneiss Complex where
531 effects of this orogeny are least modified by superimposed younger orogenic events.

532 In the Isukasian orogeny there was migmatization in the deep crust (for example,
533 fig. 3A) concomitant with low- to medium-pressure granulite facies metamorphism
534 (garnet and clinopyroxene mutually exclusive in basic compositions) and the intrusion
535 of crustally-derived granites and coeval ferrogranites (Griffin and others, 1980;
536 Nutman and others, 1996; Friend and others, 2005b). At higher crustal levels, 3.66-3.6
537 Ga was marked by intrusion of granite sheets (fig. 3B; Nutman and Bridgwater, 1986).
538 Structural studies indicate extensional deformation in both deep and upper crustal
539 levels, coeval with migmatization and intrusion of granite sheets (fig. 5). The relict ca.

3.66 Ga high pressure granulite facies (HPG) rocks found in the Isua area (fig. 6; Nutman and others, 2013) mark the switchover from juvenile crust formation to crustal recycling (fig. 4). HPG rocks form deep within tectonically-thickened continental crust during collisional orogeny (O'Brien and Rötzler, 2003). Thus we propose that at 3.66 Ga there was the start of a collision between 'blocks' of pre-3.66 Ga buoyant quartzofeldspathic crust. Closure of U-Pb titanite at 3.605 Ga in the gneisses on the north side of the Isua supracrustal belt (Crowley and others, 2002) marks the cessation of elevated crustal temperatures associated with the Isukasian orogeny. From other parts of the oldest crustal record this information has been obliterated by superimposed younger high-grade metamorphic events (for example, Crowley and others, 2002; Crowley, 2003).

After initial collision at the start of the Isukasian orogeny, greater radiogenic heat production from K, U and Th would have accelerated thermal weakening of tectonically-thickened crust, meaning that orogenic relief would have been lower (Duclaux and others, 2007). These thermal constraints would reduce the chance of early high-pressure metamorphic assemblages surviving and the muted relief would reduce the volume of extensional sedimentary basins. Consequently packages of late Eoarchean detrital sedimentary rocks of mixed provenance are rare, with only small amounts surviving in Greenland, around the outer parts of Ameralik fjord (Nutman, 2001; Friend and Nutman, 2005b).

Collision Causing the Isukasian Orogeny

Most preserved parts of Itsaia are devoid of >3.9 Ga crust. How then, does the extremely rare pre-3.9 Ga rock and zircon record fit with the formation of Itsaia? The most extensive record of pre-Itsaia terrestrial crust is held by the detrital zircon assemblages of the Jack Hills and Mount Narryer in Western Australia (see Bell and others, 2011 and references therein). Whereas the Eoarchean detrital zircons display thermal histories like the Narryer Gneiss Complex, the Hadean zircons do not, because they experienced *neither* the Isukasian orogeny *nor* the later 3.35-3.3 Ga event documented in the detrital zircon grains derived from Eoarchean crust (fig. 7).

In which case, the Hadean crust represented by the Jack Hills and Mount Narryer >4.0 Ga detrital zircons was *not* proximal to Itsaia at 3.66-3.6 Ga and was never involved in the Isukasian orogeny.

The zircon Hf isotopic record for Eoarchean detrital grains in Meso- Neoarchean metaquartzite rocks from the Beartooth Mountains of Montana (Mueller and Wooden, 2012) and for zircon populations from the Acasta gneisses (compilation in Iizuka and others, 2009) are indicated on figure 7B. They form a field indicating crust formation in the earliest Eoarchean and latest Hadean, with recrystallisation and growth from crustally-derived magmas during the Isukasian orogeny (Fig. 7B). Therefore the continental crust represented by the older Beartooth Mountain quartzite grains and the Acasta Gneisses are much better candidates than Jack Hills sources for an earliest Eoarchean to late Hadean quartzofeldspathic crustal block that participated in the Isukasian orogeny (fig. 2C).

3.53-3.46 Ga Mafic Magmatism

The 3.53-3.46 Ga geological record is dominated by basaltic to ultramafic igneous rocks formed by anhydrous decompressional partial melting (for example, Hickman and Van Kranendonk, 2012), and contrasts with the preceding few hundred million years marked by formation of crust in hydrous arc-like environments, followed by the Isukasian orogeny with crustal recycling (figs. 1 and 2). The higher MgO content of all Precambrian non-arc basalts compared with modern ones indicates they formed in a regime of higher potential mantle temperatures of up to 1500-1650°C (T_P °C), compared with ca. 1350°C for modern non-arc basalts (T_P °C = $1463 + 12.74\text{MgO} - 2924/\text{MgO}$; fig. 8; Herzberg and others 2010; Arndt, 2013, and references therein). The even higher potential mantle temperatures of >1650°C (fig. 8) required for contemporaneous Archean high-MgO komatiite liquids (for example, Bickle, 1986; Nisbet and others, 1993; Herzberg and others 2010) indicates that they must have been derived from much deeper mantle sources than those which spawned the coeval basalts.

In the Isua area of the Itsaia Gneiss Complex, 3.500-3.515 Ga Ameralik dykes are

least affected by superimposed later Archean deformation and have ultramafic, noritic
 and basic compositions and locally preserve their igneous mineralogy and texture,
 which aids in their interpretation (Gill and Bridgwater, 1979; Nutman, 1986; White
 and others, 2000; Nielsen and others, 2002; Nutman and others, 2004). Two
 ultramafic Ameralik dykes have ca. 35 and 27 wt% MgO whereas norites have 24-18
 wt% MgO (recalculated as anhydrous; from Nielson and others, 2004; Nutman and
 others, 2004). The highest-MgO Ameralik dyke (35 wt%) has a low Cr/Ni ratio of 0.7
 suggesting it could contain accumulated olivine. However the dike with 27 wt% MgO
 has a non-porphyritic texture and a Cr/Ni ratio of 3.1, within the range of Archean
 komatiite liquids (for example, Condie, 1993). This suggests this dike represents a
 liquid composition. The norites carry abundant orthopyroxene, which contains rare
 cores of corroded relict olivine. This indicates peritectic reaction of early olivine with
 a more silica-enriched liquid. The norites have elevated contents of K₂O, Rb and the
 light rare earth elements. Nielson and others (2002) proposed two petrogenetic models
 for the norites; 20% crustal assimilation by a komatiitic magma or melting of an
 'enriched' mantle containing 5% crustal component. The noritic dikes display positive
¹⁴²Nd anomalies of up to ca. 16 p.p.m. (Rizo and others, 2012), similar to that of the
 older rocks throughout the region (Bennett and others, 2007), which supports the
 contamination of high-MgO magma by local crust. Hence the ≥18 wt% MgO content
 of the norites is likely to be less than their primitive magmas. We interpret the
 ultramafic to noritic Ameralik dykes as derived from high-MgO liquids, which
 experienced variable degrees of contamination from local Itsaq Gneiss Complex crust
 during their emplacement. Their range in MgO spans that found for ca. 3.5 Ga
 komatiites, thereby suggesting similar potential mantle temperatures of >1650°C (fig.
 8; dataset for non-Ameralik dyke samples from Herzberg and others, 2010).

The geodynamic scenario for the origin of these hottest Archean high-MgO
 magmas is decompressional partial melting in plumes that rose from the core-mantle
 boundary (for example, Campbell and others, 1989; Nisbet and others, 1993). The
 question is then, what event or events triggered the ascent of hot, deep mantle at ca.
 3.5 Ga?

The Trigger for Plume Initiation at 3.53 Ga

From the study of the Phanerozoic to late Precambrian Earth, there is increasing evidence for coupling between supercontinent formation and mantle dynamics (see review in Nance and others, 2013). Phanerozoic-Proterozoic supercontinent formation-breakup cycles are rooted in non-steady-state mantle convection giving bursts of deep mantle plume activity (for example, Moyen and van Hunen, 2012). The thermal insulation effect of the assembly of continental blocks leads to temperature increases in the underlying mantle (for example, Brandl and others, 2013), causing degree-one mantle convection and fragmentation of continental domains. This fragmentation is triggered by the processes that had in the first place led to the continental assembly (Coltice and others, 2009; Burke, 2011; Burke and Cannon, 2014). This interpretation that continent formation and breakup cycles are triggered by subduction graveyard cascades into the deepest mantle is in accord with mathematical models of mantle plumes being genetically linked to subduction graveyards at the core-mantle boundary (for example, Ogawa, 2010; Tackley, 2011). Thus in the Phanerozoic and late Precambrian times where the geological record is more extensive, it is agreed that the assembly of supercontinents involved the peripheral subduction of large volumes of oceanic lithosphere (Nance and others, 2013). It is proposed that these may pond as eclogites at the 660 km mantle discontinuity, before periodically cascading to the core-mantle boundary to form slab graveyards beneath the supercontinent. Linkage between supercontinent assembly and mantle dynamics suggests that continental breakup is a natural consequence of the continental assembly that had occurred only shortly before (for example, Li and Zhong, 2009; Zhong and others, 2007).

A similar mechanism is considered plausible for the break-up of Itsaqia in the early Paleoproterozoic (fig. 2D). However, instead of the trigger being unmelted (but dehydrated) eclogitized MORB cascading into the lower mantle, we propose that the trigger for the Paleoproterozoic plume was of a cascade of high-density garnet-rich restite from the upper mantle, left over from the *partial melting* of eclogite during the

formation of Itsaia's juvenile tonalite crust. The plume initiated by this caused the break-up, partial annihilation and dispersion of Itsaia that had formed only a short time before. Evidence in support of contributions of deep-seated mantle material being sampled in the ca. 3.5 Ga plume is from the ^{142}Nd isotopic signatures of dikes speculated to be associated with Itsaia break-up. Variations in ^{142}Nd isotopic compositions arise from Sm/Nd fractionation in the first 300 million years of Earth history, whilst the short-half (68 million year) parent isotope ^{146}Sm was actively decaying. Some dykes show negative isotopic anomalies compared with modern terrestrial compositions, (Rizo and others, 2012) in contrast to the positive ^{142}Nd isotopic signatures which characterise both mafic and felsic rocks throughout the host Itsaia gneiss complex (Bennett and others, 2007) indicating an exotic mantle source.

The timescales for transport of the oldest material from the Itsaia continent to the deep mantle and return flux of material to the surface as recorded by early dikes is ca. 400 million years (from 3.9 Ga to 3.5 Ga). This is on the same time-scale as recorded in modern plume environments. For example, Wang and others (2013) document the presence of 0.5-0.2 Ga recycled material in late Cenozoic Hainan plume basalts giving a mantle circulation rate of <1 cm/yr, assuming recycled materials traveling to and returning from the core mantle boundary at 2900 km depth. This is also in accord with the observations of 0.65-0.2 Ga ages for recycled materials in the deep seated Hawaiian plume (Sobolev and others, 2011).

Position of the Paleoarchean (≤ 3.53 Ga) Plume Relative to Surviving Fragments of Itsaia

We speculate that the preserved parts of Itsaia had different positions relative to the plume that from ca. 3.53 Ga onwards generated mafic magmatism and led to the rifting that broke-up Itsaia (fig. 2D). We propose that areas such as the East Pilbara Terrane of Western Australia were located proximal to the plume head. The 3.53-3.43 Ga Warrawoona Group (Buick and others, 1995) is the oldest component of the 15-20 km thick 3.53-3.23 Ga Pilbara Supergroup (Hickman and Van Kranendonk, 2012; Van Kranendonk and others, 2014). The lowest parts of the Warrawoona Group comprise

komatiitic and basalt volcanic rocks with chert layers. Following an extensional tectonic event, the upper part consists of explosive felsic volcanic complexes of the 3.47-3.46 Duffer Formation (Hickman, 1983; Hickman and Van Kranendonk, 2004). The base of the Warrawoona Group is truncated by plutonic rocks of the granitic (*sensu lato*) Calina Supersuite (3.53-3.46 Ga) and the Tambina Supersuite (3.46-3.42 Ga; Champion and Smithies, 2007). Geochemical data indicate the derivation of the penecontemporaneous felsic volcanic and granitic rocks from the fractionation of tholeiitic parental magmas and from melting of felsic (Itsaqia?) rocks across a range of depths within the crust (Champion and Smithies, 2007; Van Kranendonk and others, 2007).

As an indication of the involvement of older crust, the >3.4 Ga plutonic rocks in the East Pilbara Terrane carry enclaves of older rocks, such as 3.66-3.58 Ga biotite tonalite gneiss within the Warrawagine Granitic Complex and xenoliths of 3.58 Ga gabbroic-anorthosite occur in 3.43 Ga granitic rocks of the Shaw Granitic Complex (McNaughton and others, 1988; Williams, 1999). Furthermore, many > 3.4 Ga East Pilbara Terrane formations carry abundant 3.8-3.6 Ga detrital zircons (for example, Van Kranendonk and others, 2002), indicating provenance from much older continental crust. The older enclaves of quartzofeldspathic gneisses plus the abundant 3.8-3.6 Ga detrital zircons suggests that the Warrawoona Group was erupted through older crust (Hickman and Van Kranendonk, 2012; Van Kranendonk and others, 2014). We suggest that this older crust was part of Itsaqia. If the East Pilbara terrane sat proximal to a plume head during the initial breakup of Itsaqia, the enormous thermal impact from the transit of komatiitic and basaltic magmas led to the almost total destruction of the Itsaqia basement, such that it was largely transformed into new granitic melts of the Calina and Tambina Supersuites.

The Ameralik dyke swarms (McGregor, 1973) were intruded into the Itsaq Gneiss Complex from 3.515-3.500 Ga (Nutman and others, 1996, 2004). The Uivak gneisses in neighboring Labrador are cut by the Saglek dikes, for which a similar age is likely. These dikes were emplaced into brittle 'cratonized' Itsaqia continental crust. Hence The Itsaq Gneiss Complex of Greenland and the Uivak Gneisses of Labrador were

peripheral to the break-up zone (fig. 2D), and consequently were affected by dike swarms of varying density but without extensive deep-crustal melting to produce coeval granitic magmas. However, examination of the large data set of SHRIMP U-Pb zircon age determinations does reveal a thermal impact, via growth of metamorphic zircon (fig. 9). This is not found in the Isua supracrustal belt area, which was at upper crustal levels at the end of the Isukasian orogeny, but in the migmatitic orthogneisses in the southern end of the Itsaq Gneiss Complex. The ‘tail’ of $^{207}\text{Pb}/^{206}\text{Pb}$ ages at the end of the Isukasian is non-Gaussian. Most distinct is a ‘spike’ of ages at 3.515-3.500 Ga (fig. 9), that coincides with the emplacement age of the oldest Ameralik dykes (Nutman and others, 2004). There is also a cluster of metamorphic zircon ages at 3.47-3.46 Ga, again indicating a thermal event in deep crustal levels, for which a distinct tectonic event has not been recognised. We suggest that this <3.52 Ga zircon growth reflects a thermal impact on the lower crust related to emplacement of the Ameralik dykes, that was insufficient to cause wholesale Itsaqia crustal anatexis, as was experienced in the East Pilbara Terrane.

In other fragments of Itsaqia Eoarchean crust such as the Narryer Gneiss Complex and in the Anshan area, ca. 3.5 Ga dike swarms have not been detected. This might be a preservation/exposure issue, but it more likely means that these Itsaqia fragments were distal from the ca. 3.5 Ga rifting axis (fig. 2D).

Mutual Exclusion of Coeval Komatiites and Arc-Related Mafic Rocks in Samples of the Oldest Geological Record

All Eoarchean mafic rocks are boninitic, picritic and tholeiitic and were formed by essentially isobaric melting of the upper mantle triggered by fluxing of fluids from ‘subducted’ crust (fig. 2A; Polat and others, 2002; Polat and Hofmann, 2003; Jenner and others, 2009). They occur with larger volumes of tonalites formed by melting of mafic crust transformed to eclogite (Nutman and others, 1999; Hoffmann and others, 2011; Nagel and others, 2012). A subduction-like environment is accepted for all these rocks (for example, Dilek and Polat, 2008). From ca. 3.53 Ga in the Pilbara (Western Australia), plume-related komatiitic and tholeiitic melts (Hickman and Van

Kranendonk, 2012) transited through basement we propose belonged to Itsaqia and largely destroyed it (fig. 2D). The 3.515-3.500 Ga Ameralik dykes of the Itsaq Gneiss Complex (Greenland) are crustally-contaminated komatiites and tholeiites (Gill and Bridgwater, 1979; Nutman and others, 2004) that we speculate were emplaced peripheral to the plume (fig. 2D). The komatiite-spawning plume was initiated by either a cascade of 300 million years' worth of sub-Itsaqia garnet-rich restites into the lower mantle or the thermal insulation effect of Itsaqia (fig. 2D). The Wilson Cycle of continent assembly and destruction can explain why coeval plume-derived komatiitic magmatism (related to continent dispersion and destruction) and arc-like mafic rocks (related to early stages of continental crust formation) are mutually-exclusive in individual fragments the oldest geological record.

Post-3.4 Ga; Wandering Itsaqia fragments

On the proviso that this synthesis for the assembly of Itsaqia by 3.66 Ga, the matching of the post 3.4 Ga events in the fragments of Itsaqia will chart the progressive breakup of what we propose here as the oldest-recognised continent. For example, the Narryer Gneiss Complex and the Anshan area rocks in China show thermal events at 3.45-3.40 Ga and ca. 3.3 Ga (fig. 1; Wan and others, 2012), suggesting they were proximal to each other until after 3.3 Ga. However, other parts, such as the Itsaq Gneiss Complex and the Uivak Gneisses do not show these events, suggesting that by 3.3 Ga they were already isolated from the Narryer Gneiss Complex and the Anshan area rocks. The fragments detached from Itsaqia were incorporated into successive continents, likely starting with Vaalbara assembled by ca. 3.0 Ga (Zegers and others, 1998).

CONCLUSIONS

A synthesis of the oldest geologic records from now globally distributed terranes reveals commonalities in their early history. A model based on the simplest scenario to explain all observations contains the following features:

- 1) Between ca. 3.9 and 3.66 Ga, formation of many convergent plate boundary

arc-like juvenile crustal assemblages caused the lateral growth of continental crust.

- 2) All fragments of Itsaqia show a common tectonothermal history at 3.66-3.6 Ga, from which we propose that in that period they were part of a single continental mass. This tectonothermal event is named the Isukasian orogeny.
- 3) The start of the Isukasian orogeny at ca. 3.66 Ga with the cessation of juvenile crust formation was caused by the start of collision between juvenile arc assemblages and another continental mass to form Itsaqia.
- 4) From ca. 3.53 Ga, the emplacement of dike swarms and the eruption of basalts and komatiites marked the breakup of Itsaqia. This initially plume-related event was likely triggered by the cascade into the lower mantle of garnet-rich restite from the formation of >3.66 Ga tonalitic crust in arc complexes.

If correct, this reconstruction of Eoarchean crustal growth, collisional orogeny and the ensuing breakup is strong evidence that some form of plate tectonics and a Wilson cycle existed by the start of the Archean,. Furthermore, the proposed geodynamic scenario can explain the puzzling absence of coeval arc-related mafic igneous rocks and plume-related komatiites in the oldest geological record.

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Figure Captions

Figure 1. Flow diagram summarizing the Eoarchaeon - Hadean geological record. The gradational red-purple of the Hadean Jack Hills zircons indicates increasing crustal reworking later in the Hadean. * Contrasting Eoarchean tectonothermal events present in the Itsaq Gneiss Complex (as indicated by red patterns) have been documented by integrated zircon U-Pb dating and metamorphic petrology (Friend and Nutman, 2005b; Nutman and others, 2013).

Figure 2. Cartoon cross-sections summarizing the proposed development of Itsaqia and its fragmentation from ca. 3.53 Ga onwards. (A and B) Crustal development in *one* of the several arc-like assemblages formed between ca. 3.9 and 3.66 Ga. (A) Shows the early stage, when initial rupture of oceanic crust permits fluid fluxing of a mantle wedge or salient, giving rise to early basalts and andesites with geochemical signatures resembling those in island arcs. (B) The dominant crust-production phase, to form large volumes of tonalite. Duplexes of underthrust oceanic(?) crust (the equivalent of modern subduction zones) invert in their base to eclogite, and with partial melting the tonalite magmas are produced. This leaves behind in the upper mantle a voluminous, dense, garnet-rich residue. (C) At ca. 3.66 Ga convergence of juvenile 3.9-3.66 Ga crust with another body of continental crust, perhaps containing Hadean components. Initial crustal thickening leads to transient high-pressure metamorphism, but orogenic collapse is marked by protracted crustal flow with migmatization at depth. We refer to this crustal reworking for ca. 50 million years as the Isukasian orogeny. (D) Accumulated garnet-rich residue from 300 million years of juvenile crustal production becomes gravitationally unstable and sinks deep into the mantle. The upward displacement of hot deeper mantle (plumes?) gave rise to basaltic and komatiitic magmas from 3.53 to 3.46 Ga. These formed the dikes and lavas at the fragmentation of Itsaqia. This development of bimodal volcanic rift associations resembles the 'universal' model of greenstone belt formation of Anhaeusser (1973). This diagram discriminates between two Archean 'greenstone' settings: (i) arc-related,

with fluid-fluxing of the upper mantle giving rise to arc-like basalts and melting of garnet bearing ‘subducted’ slab to give rise to most TTG suites and (ii) plume related involving komatiite production, extensional environments and strong modification or destruction of older felsic basement.

Figure 3. (A) Typical migmatites of the Itsaq Gneiss Complex (Google Earth™ 63°50.88’N 51°39.78’W). Tonalitic paleosome (t) occurs within schlieric granitic neosome (g). The variation in strain in the frame of view giving agmatite in the foreground and schlieric migmatites in the right background is all Eoarchean. (B) Cross-cutting relationships ca. 7 km north of the Isua supracrustal belt (Google Earth™ 63°50.92’N 51°39.89’W) – field of view ca. 3 m. The weakly-deformed tonalites (t) are cut by undeformed ca. 3.65 Ga granite sheets (g). The tonalites were cut by the 3.66 Ga (Crowley and others, 2002) mafic diorite Inaluk dykes (d), prior to intrusion of the granite sheets. Due to widespread later Archean deformation, the preservation of such relationships is rare.

Figure 4. Th/U versus U-Pb age of SHRIMP zircon analyses from the Itsaq Gneiss Complex. A.d. marks a thermal event starting from just before 3.5 Ga when intrusion of the Ameralik dykes initiated fragmentation of the Itsaq Gneiss Complex (Greenland) portion of Itsaqia. Note the continuance of high Th/U zircon *with* low Th/U zircon after ca. 3.66 Ga. This is because the intracrustal tectonothermal events led to the growth of not only sub-solidus low Th/U metamorphic zircons in palaeosome, but also high Th/U zircon grown out of granitic melts formed by crustal anatexis/recycling.

Figure 5. Early granite (g) in the ca. 3700 Ma terrane north of the Isua supracrustal belt (65°10.620’N 50°00.824’W). Note that these involve at some places *in situ* anatexis of the host tonalites (t), and the development of synplutonic ductile sigmoidal structures, whose geometry show syn-magmatic extensional deformation – see the red arrows.

Figure 6. Garnet (gnt) + clinopyroxene (cpx) + hornblende (hbl) + plagioclase (plag) + quartz (qtz) high-pressure granulite facies assemblage within banded amphibolites, north of the Isua supracrustal belt, Greenland (Google Earth™ 65°09.087'N 50°03.619'W). Subsequent retrogression has given rise to secondary amphibole (paler green) and development of epidote in surrounding plagioclase domains.

Figure 7. Zircon U-Pb age versus initial ϵ_{Hf} values for Itsaq Gneiss Complex plutonic rocks (Hiess and others, 2009, 2011; Kemp and others, 2009; Amelin and others, 2011). In (A) these are plotted with Hadean and Archean zircons from the Jack Hills and Mount Narryer (compilation from Bell and others, 2011) and in (B) with Acasta Gneisses (compilation from Iizuka and others, 2009) and Beartooth Mountains metaquartzite detrital grains (Mueller and Wooden, 2012). Open black rectangles with 'Y' 'intersection of data with orogenic events' indicates the cases where there were igneous rocks formed by melting older crust. The black rectangles marked with 'N' 'non-intersection of data with orogenic events' indicates that old crustal components did not experience tectonothermal events with growth of new zircon at that time.

Figure 8. Age (Ga) versus MgO (wt%) and calculated potential mantle temperature (T_P °C) for non-arc mafic magmas through time. Archean komatiites, Phanerozoic picrites and komatiites and non-arc basalts data compilation is from Herzburg and others (2010).

Figure 9. Compilation of 3.55-3.25 age (Ga) data of metamorphic zircons from deep crustal migmatites in the Itsaq Gneiss Complex. Tail of ages from the end of the Isukasian orogeny is non-Gaussian; there is a distinct spike at 3.515-3.500 Ga, matching the age of the oldest Ameralik dykes. Further metamorphic growth is evident at ca. 3.47-3.46 Ga. Another spike occurs at ca. 3.53 Ga, coincident with the oldest volcanic successions in Eastern Pilbara.

- (A) Anytime between 3.9 and 3.66 Ga: Rupture of 'oceanic' crust with fluxing of upper mantle to generate 'island arc' basalts

- (B) Anytime between 3.9 and 3.66 Ga: Partial melting of eclogite to generate tonalite-dacite complexes

- (C) 3.66-3.60 Ga Isukasian collisional orogeny creating Itsaia: Crustal thickening followed by orogenic collapse and crustal melting

- (D) <3.53 Ga Rifting of Itsaia: Cascade of garnet-rich restite to bottom of mantle triggered a plume. Extension of Itsaia, with komatiite to rhyolite volcanic sequences. Over rift node, Itsaia is destroyed

komatiites and basalts	juvenile tonalite-dacite
mafic dikes	eclogite and restite
felsic crustal melts	'island arc' basalts
late Hadean - Eoarchean impactor	'oceanic' crust
active fault	old fault

g

t