DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2001/131

Isua workshop, Berlin 17 to 20 january 2002

Harnack Haus, Berlin, programme and abstracts

Peter W.U. Appel and Stephen Moorbath

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF ENVIRONMENT AND ENERGY

G E U S

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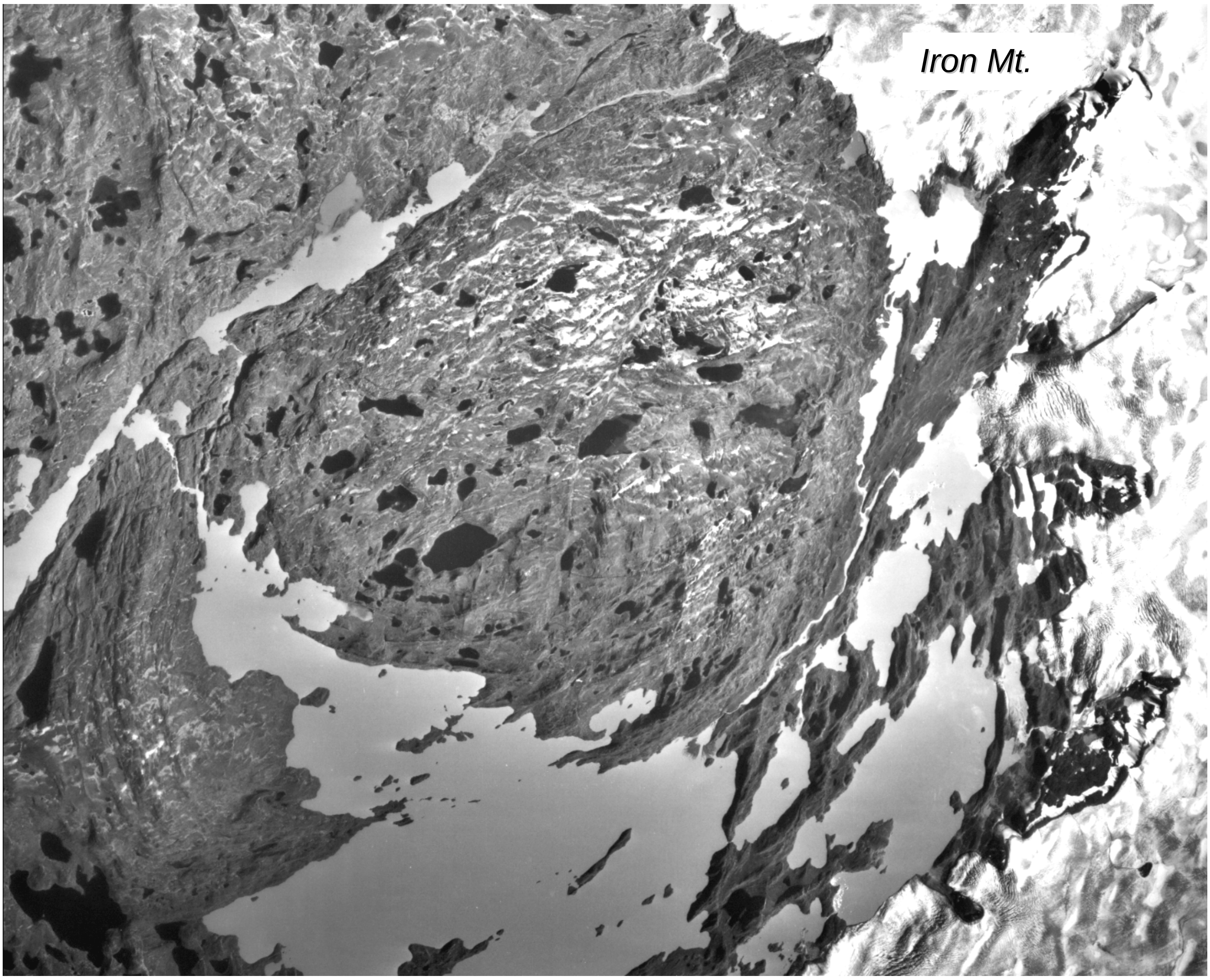
MINISTRY OF ENVIRONMENT

GEUS

Contents


Iron Mt.

The Isua Multidisciplinary Research Project (IMRP) 1997 – 2001

The present volume contains Abstracts of lectures presented at a Workshop of IMRP participants at the Harnack Haus Conference Centre of the Max-Planck-Gesellschaft in Berlin during 17 – 20th January, 2002. The Workshop was held to mark the termination of official funding for the IMRP and to present some of the scientific results obtained during the previous four years by an international group of scientists working in loose affiliation. Of other groups working in the Isua region, there was also representation from the Geological Museum and the Danish Lithosphere Centre.

The IMRP was funded during 1997 to 2001 by the Geological Survey of Denmark and Greenland (GEUS), the Danish National Research Council, the Commission for Scientific Research in Greenland, and the Greenland Bureau of Minerals and Petroleum (formerly the Minerals office). IMRP support was provided for essential helicopter transport throughout each summer field season, for camping costs in Greenland, and for shipment of samples to laboratories world-wide. Generous support to IMRP has also been received from the National Geographic, the Max-Planck-Institut für Chemie, Mainz, and the National History Museum, Ontario.

Since the first realisation of the scientific importance of the Isua Greenstone Belt (IGB) for early Archaean studies in 1971, many workers have published research papers on varied aspects of the belt, whilst a geological map of the whole Isua region was published by the Geological Survey of Greenland in 1986. In the early- to mid - 1990's it became clear to us that some of the older work on the IGB, as well as the published map, were in need of major revision. In addition, several lines of current research had never been applied to IGB rocks. It was therefore decided to seek funds from the organisations listed above for a renewed and more intense round of field work to, firstly, revise the published geological map and, secondly, enable international scientists from a wide range of disciplines to visit the Isua region and to collect samples under expert geological guidance for multidisciplinary laboratory studies. The following Abstracts contain a cross-section of work mostly done under the auspices of the IMRP.

Peter W. U. Appel
Stephen Moorbath

John Myers, Al Hofmann, Stephen Moorbath, Keith O'Nions and Chris Fedo at Iron Mt. 1997

Sessions at the workshop

	Allocated time
Welcome Peter Appel	10 + 5
General Introduction Stephen Moorbath	20 + 10
1. Cosmology	
Gustaf Arrhenius	20 + 10
Uffe Gråe Jørgensen	20 + 10
2. Early life	
Minik Rosing	20 + 10
Frances Westall	20 + 10
Peter Appel	10 + 5
Mark van Zuilen	20 + 10
Aivo Lepland	20 + 10
3. Geophysics	
Thorkild Rasmussen	20 + 10
4. Geochemistry	
Jacques Touret	20 + 10
Ali Polat	20 + 10
Balz Kamber	20 + 10
Ali Polat	20 + 10
Martin Whitehouse	20 + 10
5. Radiogenic isotope geochemistry	
Al Hofmann	20 + 10
Balz Kamber	20 + 10
Jan Kramers continental growth	20 + 10
Yuri Amelin	20 + 10
Jan Kramers Early atmosphere	20 + 10
6. Stable isotope geochemistry	
Harald Strauss	20 + 10
Nathalie Grassineau	20 + 10
Michael Wiedenbeck	20 + 10
7. Structural and metamorphic geology	
Hugh Rollinson metamorphism igb	20 + 10
Peter Appel chromite	20 + 10
Hugh Rollinson dunite	20 + 10
Steve Temperley	20 + 10

8. Poster session

Peter Appel	Poster
Sandra Kamo	Poster
David Lowry	Poster
Inna Mudrovska	Poster
Sune Nielsen	Poster
Roz White	Poster

Schedule

Thursday 17 January 2002

19^{30}	Ice breaker party

Friday 18 January 2002

9^{00} – 9^{15}	Welcome Peter Appel
9^{15} – 9^{45}	General introduction Stephen Moorbath
9^{45} – 10^{15}	Gustaf Arrhenius to be held by Aivo Lepland
10^{15} – 10^{45}	Uffe Gråe Jørgensen
10^{45} – 11^{00}	Coffee
11^{00} – 11^{30}	Minik Rosing
11^{30} – 12^{00}	Frances Westall
12^{00} – 12^{15}	Peter Appel
12^{15} – 12^{45}	Mark van Zuilen
12^{45} – 14^{00}	Lunch
14^{00} – 14^{30}	Aivo Lepland
14^{30} – 15^{00}	Thorkild Rasmussen
15^{00} – 15^{30}	Jacques Touret
15^{30} – 16^{00}	Coffee
16^{00} – 16^{30}	Ali Polat
16^{30} – 17^{00}	Balz Kamber
17^{00} – 17^{30}	Ali Polat

Posters
Peter Appel
Sandra Kamo
David Lowry
Inna Mudrovska
Sune Nielsen
Roz White

18^{30} – 20^{00}	Dinner
20^{00} - ??	Tales of Field work in West Greenland

Informal, illustrated presentation and discussion of geological and non-geological experiences by Workshop participants in the Isua and Godthaabsfjord regions over the past few decades. Please bring your scenic and geological transparencies and photographs. We hope you will all attend and contribute to an entertaining and nostalgic evening.

Saturday 19 January 2002

$9^{00} – 9^{30}$	Martin Whitehouse
$9^{30} – 10^{00}$	Al Hofmann
$10^{00} – 10^{30}$	Balz Kamber
$10^{30} – 11^{00}$	Coffee
$11^{00} – 11^{30}$	Jan Kramers Continents
$11^{30} – 12^{00}$	Yuri Amelin
$12^{00} – 12^{30}$	Jan Kramers Early atmosphere
$12^{30} – 14^{00}$	Lunch
$14^{00} – 14^{30}$	Harald Strauss
$14^{30} – 15^{00}$	Nathalie Grassineau
$15^{00} – 15^{30}$	Michael Wiedenbeck
$15^{30} – 16^{00}$	Coffee
$16^{00} – 16^{30}$	Hugh Rollinson metamorphism
$16^{30} – 16^{45}$	Peter Appel chromite
$16^{45} – 17^{15}$	Hugh Rollinson chromite
$17^{15} – 17^{30}$	Steve Temperley
$19^{30} – 20^{00}$	Drinks
20^{00} - ?	Banquet

Sunday 20 January 2002

$10^{00} – 11^{00}$	What is next? A one hour discussion on future research programmes in the Isua region.

View from Isua Iron Mountain towards Nuuk

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Chairpersons Berlin Workshop

Friday 18 January 2002

9^{00} - 10^{45}	Balz Kamber
11^{00} - 12^{45}	Jacques Touret
14^{00} - 15^{30}	Minik Rosing
16^{00} - 17^{30}	Hugh Rollinson

Saturday 19 January 2002

9^{00} – 10^{30}	Yuri Amelin
11^{00} – 12^{30}	Martin Whitehouse
14^{00} – 15^{30}	Sandra Kamo
16^{00} - 17^{30}	Stephen Moorbath

Practical Details

We have reserved Harnack Haus from 17th January. Official check-in time is 14.00 h. Participants can arrive at 08.00 h when the reception opens and can move in as far as rooms are already available. Departure Sunday 20th January. Check-out is at 11^{00} in the morning. Luggage can be stored at the reception if necessary. For further details on the conference centre see: http://www.harnackhaus-berlin.mpg.de

You are kindly requested to send informations as to when you expect to arrive at the Harnack Haus and which nationality you have to pa@geus.dk. I need these informations not later than one week ahead of the workshop.

How to find the Harnack-House

Distances

Tegel Airport	18 km
Station Zoologischer Garten	10 km
Kurfürstendamm	8 km
Berlin Museums	1 km
Subway station Thielplatz Line 1	0,1 km

From Tegel Airport

with the 109 bus (in the direction of Zoologischer Garten) to Jacob-Kaiser-Platz. There, transfer to the subway line 7 (U7 in the direction of Rudow) to Fehrbelliner Platz. There, transfer to the subway line 1 (U1 in the direction of Krumme Lanke) to Thielplatz. The Harnack-Haus lies to the left of the station about 100 meters away.

From Bahnhof Zoologischer Garten

with subway line 9 direction Rathaus Steglitz to Spichernstraße. Get off at Spichernstraße and switch trains to U1 direction Krumme Lanke. Get off at Thielplatz. The Harnack-House lies to the left of the station about 100 meters away.

By car

with the Autobahn 115 to the Hüttenweg offramp, turn right and go in the direction of Dahlem to the corner of Clayallee, right again, then turn left into Saargemünder Strasse and shortly thereafter is the Ihnestrasse. The Harnack-House is on the corner of Ihnestrasse and Saargmünder Strasse.

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Abstracts

Amelin & Kamo

U-Pb ages of titanite and metamorphic history of 3.9-3.6 Ga gneisses south of the Isua Greenstone Belt

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Titanite is a common accessory mineral in felsic rocks and is a widely used U-Pb geochronometer for metamorphic processes. Previous studies of titanites from various parts of the Itsaq Gneiss Complex have shown that the U-Pb age distribution varies greatly with location within the Complex. Titanites from the Central Gneiss Dome, an area enclosed by the Isua Greenstone Belt (Baadsgaard 1983), and from the area adjacent to the Isua Greenstone Belt (Amelin 2000a,b) form linear arrays in concordia diagrams. Upper and lower intercepts of ca. 3.6 Ga and 2.7 Ga are interpreted as the timing of two metamorphic episodes. Recently, Crowley and Myers (2001) reported titanite ages of 3606 Ma from the Central Gneiss Dome and 2915 Ma from the gneisses adjacent to the belt. In contrast, the early Archean gneisses of the Nuuk area contain titanite with 2.5-2.6 Ga U-Pb systems (Baadsgaard et al. 1976, Amelin 2000a,b).

Single-grain dating of titanites from the vicinity of the Isua belt (Amelin 2000a) showed that the titanite populations are heterogeneous on the intra-grain scale, and a small fraction of grains preserve almost undisturbed 3.6 Ga U-Pb systems. Combined Sm-Nd and U-Pb analyses allowed the determination of precise and tenable initial Nd values for early Archean gneisses from titanite grains formed during an early metamorphism that were not disturbed later. This approach can be used even if early Archean grains represent a small fraction of an otherwise young or altered titanite population.

In the next stage of the study we attempted to use the same approach to determine the initial Nd isotopic signatures, independent of the whole rock closed system assumption, from the 3.9-3.6 tonalitic gneisses located south of the Isua belt. These gneisses are predominantly 3.8 Ga old (Nutman et al. 1999), but both older and younger meta-igneous rocks are present (Crowley and Myers 2001, Kamo et al. 2002). Evidence for the presence of local low strain zones (Nutman et al. 1999) and occurrence of 3623 Ma titanite along with younger titanite (Crowley and Myers 2001) suggested that this approach might be applicable to the rocks in this area.

Titanites were recovered from four gneiss samples, collected from the area within 3-5 km of Nutman et al.'s (1999) localities 'A' and 'B' (see companion abstract by Kamo et al. for more details about samples). In all four samples, titanite grains vary in color from dark-brown to almost colourless. In two of the samples, SK00-09 and SK00-11, titanite populations are also heterogeneous in age from 2.68 to 2.60 Ga. In both cases darker grains have higher U concentrations and an older age. The model Th/U ratios are high and relatively homogeneous within the sample (Th/U=2.3-3.9 for SK00-09 and 1.6-2.0 for SK00-11).

These data suggest a complex late Archean metamorphic history of the southern gneisses, with at least two episodes of titanite growth and/or resetting.

The other two samples, SK00-10B and SK00-04, contain titanite populations that appear heterogeneous but have low Th/U (0.6-1.0 and close to zero, respectively), and homogeneous 2.60-2.62 Ga U-Pb systems. Their U-Pb systems resemble those in titanite from an augen gneiss of the Nuuk area (Baadsgaard et al. 1976, Amelin 2000a,b).

Preserved early Archean titanite grains, suitable for initial Nd ratio determinations were not found in any of the studied gneisses. Nevertheless, the report of 3623 Ma titanite from the same area by Crowley and Myers (2001) is encouraging. Thus, a search for better preserved 3.8 Ga or older rocks which can be used for a comparative Sm-Nd and U-Pb study of whole rocks and accessory minerals may help resolve the controversy of the significance of early Archean initial Nd isotopic values and will continue in the future.

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A.P.Nutman, V.C.Bennett, C.R.L.Friend and M.D.Norman (1999) Meta-igneous (non-gneissic) tonalites and quartz-diorites from an extensive ca. 3800 Ma terrain south of the Isua supracrustal belt, southern West Greenland: constraints on early crust formation. Contrib. Mineral. Petrol. **137**, 364-388.

Appel et al.

Complex chromite textures reveal the magmatic evolution of an early Archean layered ultramafic body in West Greenland

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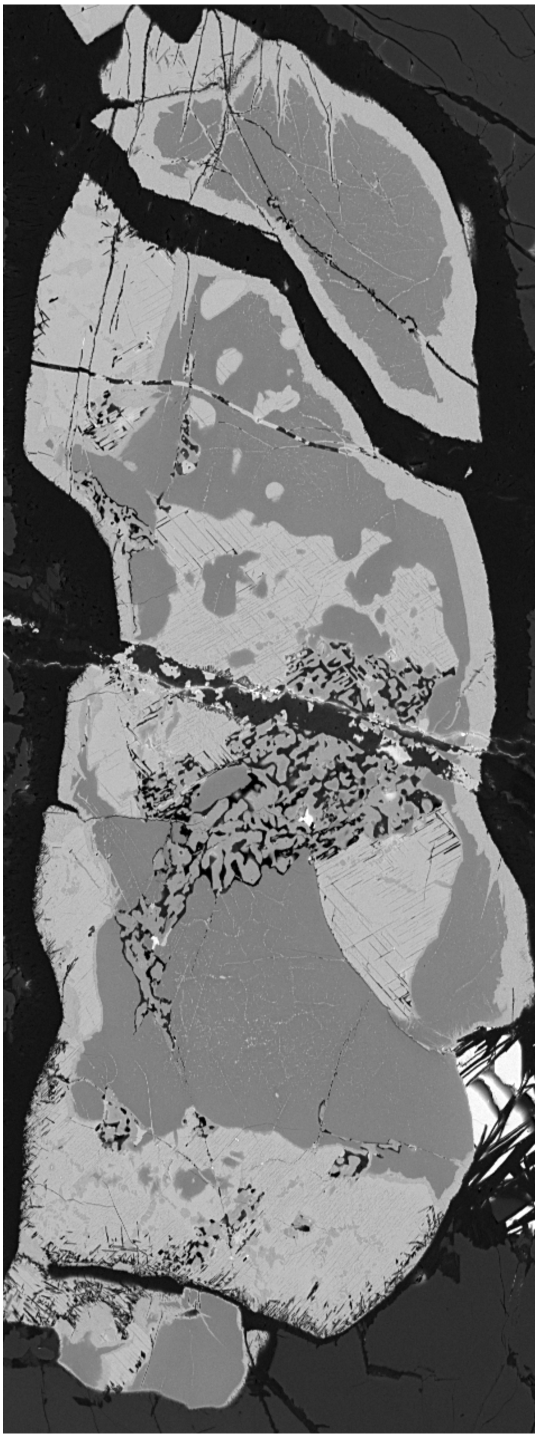
Massive chromitite, banded chromitite and disseminated chromite grains are found in a ~3800 Ma layered ultrabasic body in West Greenland. The ultrabasite is dominated by dunite. In the upper exposed part harzburgite and sheets of gabbro-anorthosite occur. The chromite grains in the dunites, and in the massive and banded chromitites are homogeneous (Fig. 1), with increasing Fe-contents upwards in the intrusion. In the harzburgites chromites show unusual and very complex textural relationships, with two generations of chromites one replacing the other, and both exhibiting exsolution textures. In the harzburgites, an Fe-rich chromite crystallised first, subsequently exsolving two spinel phases in a very fine-scale pattern and ilmenite lamellae in a trellis pattern. The Fe-rich chromite was later partly replaced by Al-rich chromite (Fig. 2), which crystallised contemporaneously with formation of a late gabbro-anorthositic melt. During cooling, the Al-rich chromite exsolved a very fine-scale magnetite-rich phase. The exsolutions in the first generation chromite were formed under magmatic conditions. The exsolution of ilmenite lamellae in the Fe-rich spinel was caused by oxidation under magmatic conditions.

During metamorphism a mineral paragenesis was formed in the sheets of gabbro anorthosite, with plagioclase, pargasitic amphibole and ruby corundum. This assemblage closely resembles the mineral assemblage developed during metamorphism of the upper part of the Fiskenæsset anorthosite complex. Sapphirine and korneruppine has not yet been found in the present metamorphosed gabbro anorthosites.

At a late stage brittle deformation affected the ultramafic complex and fractured some of the chromite grains. Small scale alteration of the chromite grains along the cracks took place producing a peculiar myrmekitic texture (Fig. 3) with chromite and magnesite or brucite (Fig. 4).



Complex chromite textures

Chromitite

Massive chromitite

Banded chromitite

Thin patch of chromitite

Massive chromitite intruded by dunite

Appel

Possible immiscibility structures in pillow lavas in the Isua Greenstone Belt, West Greenland

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In low strain areas of the Isua Greenstone Belt (IGB), well preserved volcanic structures are frequently observed. The most common are pillow structures with fine-grained dark grey to black rims and light grey centres. Pillows range up to well over 1 metre in length and 50 centimetres in breath. Less frequent pillow breccia and debris flows with fragments of pillows and sediments are found (Appel et al., 1998). In some pillows amygdales have been preserved. They are mostly filled with quartz, but sometimes also with carbonate. The amygdales are 1 to 3 millimetres in diameter. They are irregularly distributed in the interior of the pillows.

In the eastern and western part of the IGB problematic structures have been observed in pillow lavas and in thin lava flows. These structures are provisionally termed ocelli although they do not fit the definition of ocelli.

The ocelli are light grey ellipsoidal to irregular in outline ranging in size up to 8 cm. They are often scattered within pillows. Sometimes, however, they occur exclusively right inside the fine-grained cooling rim of the pillows, and sometimes in the central part of the pillows, where they locally make up more than 80 vol. %. The host pillow is here termed matrix. Amygdales are found in both matrix and ocelli.

Ocelli consist of plagioclase, quartz and amphibole in a saccharoidale-to-interlocking texture. They do not show any zoning or concentric structures. The ocelli are set in a matrix of amphibole and plagioclase. They are always fine-grained compared with the medium-grained matrix. Ocelli and matrix have small amounts of ilmenite.

Chemical composition of ocelli and matrix was estimated by analyses with the Scanning Electron Microscope (SEM) equiped with an energy dispersive X-ray spectrometer (EDS). EDS analyses were made without standards on polished thin sections in areas of $500\mu m^2$. The chemical composition of the ocelli vary somewhat from one sample to the next (Table 1), and also within each sample. Four ocelli were analysed in sample 465501. Most elements vary by 1-2% percent except for Ca, wich varied from 4.4 to 8.4% (CaO). This may reflect later influx of carbonate during the abundant carbonate alteration seen in many rock units in the IGB (Rose et al. 1996).

The average matrix composition varies from one sample to the next (Table 1), and internally there is considerable variation in most elements. It probably results from occurrence of late veinlets filled with quartz and/or carbonate. The composition of ocelli and matrix is plotted in a triangular diagram (Fig. 1). In Fig. 1 is also seen ocelli-matrix pairs from high-Mg basalts in the Ventersdorp Supergroup (Cawthorn et al. 1979). The similarity of the field occurrence of the Ventersdorp ocelli and the chemistry of ocelli-matrix pairs at IGB and Ventersdorp is striking.

It is suggested that Isua ocelli represent immiscible blobs from an acid magma The blobs were carried to the surface with the mafic magma and subsequently solidified within pillows and thin lavaflows. If this interpretation is correct the acid phase may carry zircons, which could yield a direct age magmatism within the IGB.

Sample	SiO_2	Al_2O_3	MgO	CaO	Na_2O	Fe_2O_3	TiO_2	K_2O	P_2O_5
465501 oc	64.2	18.2	0.8	5.7	7.0	2.2	0.5	0.3	1.1
465501 ma	49.2	9.7	10.5	11.0	1.1	16.9	1.0	0.5	0.1
465502.1 oc	70.5	12.7	2.8	4.6	4.9	4.0	0.6	0.0	0.0
465502.1 ma	46.8	9.9	12.6	11.7	1.2	17.2	0.7	0.0	0.0
465605b oc	68.5	13.7	2.3	6.1	5.2	3.6	0.7	0.0	0.0
465605b ma	50.2	9.3	10.3	11.6	1.3	16.9	0.5	0.0	0.0
465605a oc	68.7	11.4	3.5	6.1	4.2	5.4	0.6	0.0	0.0
465605a ma	49.5	8.8	10.6	12.0	1.1	17.0	0.7	0.3	0.0
465614 oc	69.3	11.4	3.1	6.2	4.7	5.1	0.5	n.d.	n.d.
465614 ma	50.5	8.3	11.3	11.4	1.3	16.5	0.7	n.d.	n.d.
472819 oc	72.0	13.7	2.3	5.5	2.7	3.4	0.4	n.d.	n.d.
472819 ma	49.0	20.3	8.7	8.6	2.5	10.6	0.3	n.d.	n.d.
465620 oc	70.7	14.1	0.6	6.3	4.8	1.3	0.7	0.0	1.6
465620 ma	46.6	11.4	11.0	10.9	1.1	16.9	0.9	1.2	0.0

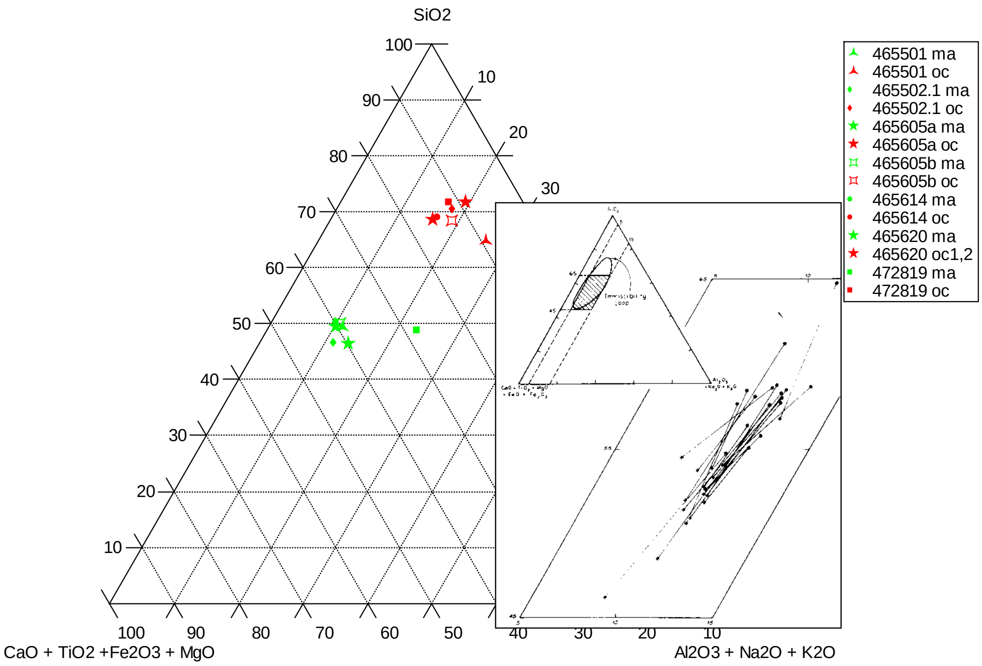

Fig. 1 Major element composition of ocelli (oc) and pillow matrix (ma). Inset from Cawthorne et al. (1979). Tie lines join coexisting ocelli (circles) and matrix (crosses) compositions. The shaded area of the inset shows the immiscibility loop from Roeder (1951).

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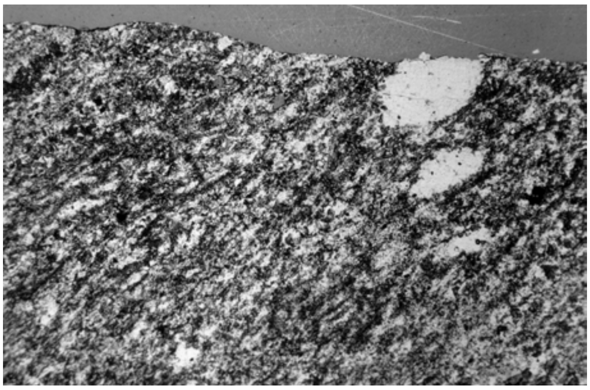
Deformed flattened ocelli in thin lava flow

Less deformed ocelli in thin lava flow



Part of an ocellus with three quartz-filled amygdales

Isuasphaera isua (Pflug) revisited

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In 1978 and 1979, H. D. Pflug claimed to have found fossils in a sample of metachert from the 3.7-3.8 Ga Isua Greenstone Belt, West Greenland (Pflug 1978; Pflug and Jaeschke-Boyer, 1979). The fossil was named Isuasphera isua and occurred as small black spherical objects in quartz grains. Pflug's interpretation was seriously challenged by Bridgwater et al. (1981) and by Roedder (1981). The former claimed that the putative microfossils are indistinguishable from limonite-stained fluid inclusions of inorganic and post-depositional origin. Roedder (1981) claimed that Pflug's microfossils are limonite-stained cavities, which stem from dissolution of dolomite grains. Recently Pflug (2001) published another account of his discovery, but without mentioning the very convincing arguments raised by Bridgwater et al. (1981) and by Roedder (1981).

Neither Pflug nor his critics had ever seen the outcrop from which the sample was collected. We revisited the outcrop during the field season of 2001. The outcrop is a strongly weathered, extremely deformed (rodded), highly metamorphosed chert. The strong rodding, which is clearly seen on Fig. 1, makes it obvious that any spherical object deposited on the sea-floor during precipitation would have been stretched almost to infinity during deformation and could not possibly appear as a spherical body today. Thin sections clearly show extreme elongation of minerals and complete recrystallisation of quartz grains, as well as large numbers of small spherical limonite-stained cavities. These cavities occur in quartz and amphibole grains.

The sample is from a rock surface and shows a sugary texture due to strong surficial weathering. The outcrop is at/or very close to the pre-Quaternary peneplain and has thus been exposed to several millions years of weathering under desert-like conditions, as witnessed by abundant silcrete boulders found in that part of the Isua area.

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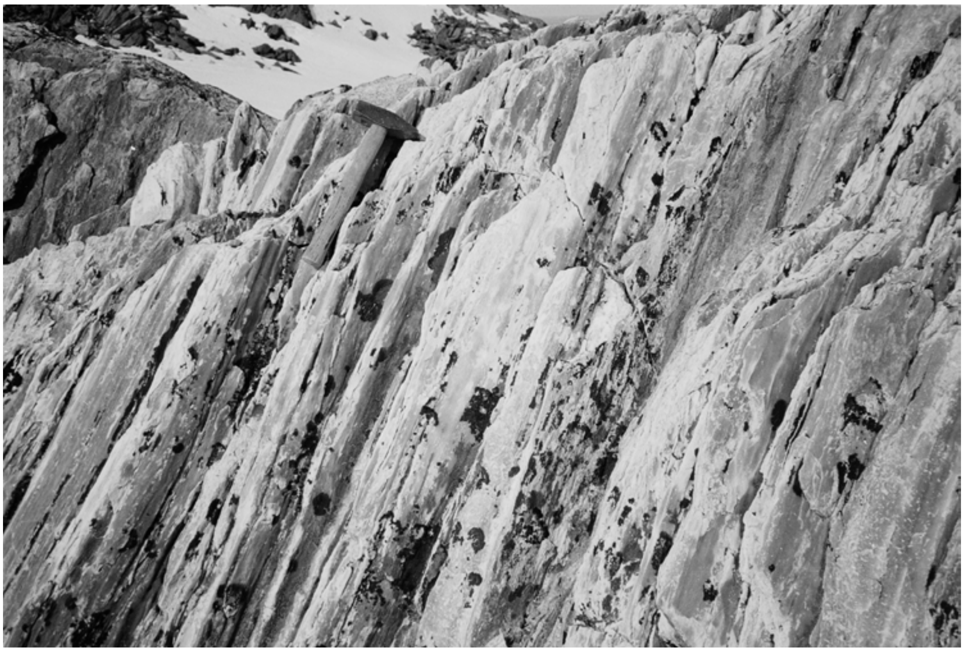

Metachert. The sample in which Pflug claimed to have found the microfossil Isuaspheara isua (Pflug) is from this outcrop. The rocks are strongly rodded parallel to the hammer handle. The rocks are furthermore strongly affected by surface weathering.

Arrhenius et al.

Search for an Extraterrestrial Impact Record in Isua Sediments

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The cratering record of impacts on the Moon has led to the common belief that the Earth must have experienced an even stronger, gravitationally enhanced late bombardment, culminating around 3.8 Ga and extending to about 3.5 Ga. However, no evidence for such violent impacts has been found in the terrestrial rock record.

The sedimentary sequences in the ca. 3.8 Ga Isua supracrustal belt (ISB), overlapping in time with the tail end of the late lunar bombardment period, contain structural disturbances but they are not clearly impact related. One of the most notable features is seen at the north-eastern end of the ISB where strongly disturbed 0.1-1 m thick layers of banded iron formation (BIF) are sandwiched between undisturbed, finely laminated strata. These disturbances probably represent shear zones formed during small scale tectonic translations parallel to the bedding. However, some of the thicker packages display grading of the component rock fragments, opening the possibility that they could be surge deposits formed by fierce resuspension and sorting during resettling.

In order to test the possibility of an impact related origin of such disturbed BIF sections we have analysed 17 samples for their Ir concentration with particular attention to the stratigraphic variations in a 1m thick graded sequence (9 samples). Ir concentrations together with Ce, Co, Cr, Cs, Eu, Fe, Ni, Rb, Sb, Sc and Tb were measured using the Luis W. Alvarez Iridium Coincidence Spectrometer with an ~ 5 parts per trillion (ppt} detection limit for Ir. The measured Ir concentrations are well below average crustal abundance (~ 50 ppt) in all samples, ranging from below detection limit to 12 ppt. The Ir concentrations in the graded sequence do not show any meaningful trends, nor is there any systematic contrast between Ir values in disturbed and undisturbed layers, including the sediment strata immediately overlying the graded bed.

The exceptionally low Ir abundances in analysed BIF samples would seem to be inconsistent with a high flux rate of extraterrestrial material during accumulation of Isua sediments placing our study in the group of several recent unsuccessful attempts to establish an impact record in the oldest terrestrial rock record. Attempts to explain this apparent discrepancy with the record from the Moon include the likely assumption that substantial time intervals between major impacts would allow long, quiescent sedimentary intervals, leaving impact breccias and surge deposits easily missed in the fragmentary record. This argument does, however, not affect the consideration of a continually enhanced population of collisional dust that is assumed to have accompanied bombardment by marauding asteroids through the entire inner solar system, and that would be evident in an enhanced persistent flux of extraterrestrial dust to the Earth.

Other suggestions for the missing dust- and impact features make inconsistent reference to the lunar record by assuming that the late lunar bombardment ceased 3.8 Ga ago, ignoring the fact that it continued at a decreasing rate with major impacts occurring as late as about 3.5 Ga.

Grassineau et al.

Sulphur, Carbon and Oxygen Isotopic Results for the Isua Greenstone Belt, West Greenland: Evaluating the Sources of Components in Mineral Deposits

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The Isua Greenstone Belt (IGB) in West Greenland, with ages from 3.65 to 3.8Ga hosts numerous sulphide mineralisations (Appel, 1979) and therefore research into early life using sulphur isotopic compositions have been carried out (Monster et al., 1979; Strauss, 1999). Samples of stratabound iron- and copper sulphides in mafic volcanic rocks were measured and gave a narrow range around ±0‰, which indicated that no sulphur bacteria were active in the early Archaean. Likewise, carbon isotopic studies on Isua IGB were also undertaken showing better evidence of early life (Schidlowski, 1979; Hayes, 1983; Rosing, 1999). Sulphur deposits are often associated with gold across the IGB, with high Au concentrations for some of them (Appel, in press).

In this study, sulphur, carbon and oxygen isotopes have been analysed from samples across the IGB. The results show a wide range of ^{13}C from –30 to +2‰ in carbonates and reduced carbon. The composition of the reduced carbon in the sedimentary sequences varies from –30 to –6‰, suggesting that bacterial reduction was taking place at the time. The sulphur isotopic range is wider than previously obtained, and covers values between –10 and +4, for various sulphide deposits, including the late mineralisations at 2.7Ga (Grassineau, 2000). The sedimentary sequences, mainly BIF, show a wider range in the eastern part (-4 to +4‰) than the western one. However, it is in the SW of the IGB that the lightest values have been observed in two very specific mineral deposits (-10 to –4‰).

Two periods of sulphide mineralisation seem to occur in the western part of the belt, including a gold deposit in association with sulphide minerals and metal-rich concentrations in a thick intrusive sheet of tonalite gneiss (Appel, 2000). This mineralisation may have been mobilised as early as 3.8Ga (Frei et al., 2001). Sulphur and oxygen analysis have been carried out in order to determine the processes involved in its formation. Oxygen isotopic thermometry suggests a temperature of 400˚C for the last metamorphism of the tonalite sheet, but the sulphide mineralisation took place later at a lower temperature and in

an open system. The source of the sulphur comes from the great reservoir that constitutes the IGB, such as mafic pillow-lavas (0 to +1‰). Hydrothermal metal- and sulphur-rich fluids passed across the IGB, precipitating pyrite in the BIF. The remaining fluid was depleted in Fe and 34S, with high concentrations of Pb, Zn, Cu and other heavy metals. With the decrease of the temperature of the fluids, Pb precipitated together with Zn and the other rare metals, giving depleted δ34S around -4.5‰ in the tonalite sheet.
The final hydrothermal event occurred at 2.7Ga, and remobilised some part of the sulphur hosted in the IGB. Sulphides precipitated in association with fuchsite crystallisation in several places of the belt. δ34S of pyrite from these deposits shows a wide range from –10 to +3‰. However, locally the deposits reveal more restricted ranges, despite the original source of sulphur and metals being most likely magmatic.
Sulphur isotopic compositions obtained in this study record the regional events which affected the IGB in early and middle Archaean times.

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Jørgensen & Appel

Cosmic origin of the Earth's water

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We have collected samples at two different locations in the Isua Greenstone elt, with the aim of shedding more light at the questions of the amount and the nature of the cosmic impacts during the end of the formation of the Earth.

The standard theory for the formation of the planets tells us that a large interstellar cloud collapsed and formed a gas disk around the forming proto-sun. Radiative cooling allowed gas in the disk to condense to small dust grains, which gravitationally settled to the mid-plane. Here they collided and coalesced to form solid bodies of growing size, which by

definition, are called planetesimals when they reach a certain size. In this scenario we should expect the collision rate (which is equal to the impact rate in the end of the planetary formation period) to be a monotonically decreasing function of time, as an increasing fraction of the available solid material in the disk is swept
up by the planets.

The many craters on the surface of the Moon (and the corresponding crater distribution on Mars and Mercury) are clear witnesses of the violence of the final assembling of the terrestrial planets.
The craters obviously represent the final impact events, but it is not clear what kind of cosmic material caused them, where this material came from, how the impacts were distributed as a function of time, and to which degree the lunar crater distribution also represents the terrestrial
impact rate.

Dating of the rocks brought back by the Apollo mission points at a sharp peak in the lunar impact rate approximately 3.9 Gyr ago, and studies of lunar meteorites also point at a peak in the impact rate, but favour a distribution which was much broader in time than infered from the Apollo data,
and which continued with relatively many impacts until as recently as 3.2 Gyr ago. This crater forming period of the creation of the planets and the Moon, is usually referred to as the late heavy bombardment period. If the lunar impacts are representative for the terrestrial impacts too, we see
that one set of the lunar data (the meteorites) predicts a substantial terrestrial impact rate during the Isua Greenstone Belt formation 3.8 Gyrs ago.If these impacts represent the ending of the period of the planetary sweeping up of the solid material in the proto-planetary disk, the Isua material is expected to be rich in iridium.

Another possibility for the origin of the late heavy bombardment is that it represents the fast final growing phase of the outermost giant planets, Uranus and Neptune. During this phase the two planets are believed to have perturbed a large number of planetesimals from the outer solar system -- comets -- into the inner solar system. These comets are likely to not have been iridium-rich. If these comets are responsible for the late heavy bombardment, they will also have contributed with a substantial fraction to the formation of the Earth's oceans, which will be reflected in differences in the deuterium to hydrogen ratio of the present ocean compared to the ocean which existed at the time of the formation of Isua.

We are therefore now combining measurements of the iridium content and the deuterium to hydrogen ratio from samples collected in 2001 at two specifically favourable locations in the Isua Greenstone Belt. The samples from which the iridium abundance is being measured are collected from clearly undeformed sedimentary chart, while the deuterium to hydrogen ratio is measured from material containing traces of water from the original ocean.

Kamber et al.

Longevity of Hadean crust: Evidence from Pb-isotopes of IGB lithologies and TTG gneisses to the south of the IGB

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Crust must have encased the Earth's surface soon after accretion (i.e. within 100 Ma from the collapse of the inner solar nebula) yet there is apparently no direct record of the rocks that formed the earliest crust. While detrital zircons of up to 4.4 Ga have been found in much younger sedimentary rocks the general paucity of terrestrial material exceeding an age of 3.8 Ga illustrates that preservation potential of the early terrestrial crust was poor. Thus, the fundamental questions regarding composition and formation mechanism of Hadean crust remain unresolved.

Our most promising source of evidence is the isotopic memory of the oldest isotopically intact terrestrial rock samples, which may yield a record of source depletion or enrichment. In other words, the isotopic memory of the source from which the oldest preserved rocks formed should allow us to make inferences about the existence, nature, and possibly the age of unpreserved Hadean crust. For example, depletion could have occurred in the convecting mantle, which would imply early (> 4.2 Ga) formation and comparatively long (> 200 Ma) preservation of significant amounts of evolved proto-crust. Alternatively, if the source of the oldest rocks was enriched it could indicate existence of thick basaltic crust (sometimes called 'oceanic' plateau) whose creation may not have significantly depleted the mantle. We propose that the Pb-isotope systematics of the Isua Greenstone Belt (IGB) and rocks from the area immediately to the south of the IGB, a terrain which we informally call South Of Isua (SOI), contain a memory of coexistence of an undepleted mantle and an isotopically evolved crust of largely basaltic composition, which we argue to be typical Hadean crust.

We report a large set of Pb-isotope data for early Archaean TTG gneisses and amphibolites from the SOI area. Initial Pb-isotope ratios of leached feldspars of both lithologies define tight linear arrays in common Pb space. The slope of the TTG feldspar regression line (22 samples) yields an apparent age of 4480±77 Ma, and that of interleaved amphibolites (7 samples) corresponds to a date of 4455±540 Ma. The regression lines have no direct age significance because they are palaeo-isochrons that formed due to feldspar-whole rock Pb-isotope homogenisation at ca. 1.8-2.0 Ga. However, the feldspar palaeo-isochrons do provide indirect support for the claimed early Archaean crystallisation ages of the igneous precursors to these gneisses. In particular, the slope of the tight regression line for the tonalite samples from the SOI area is in good agreement with our new 3.81 Ga and published

3.80-3.82 Ga U-Pb ion probe zircon dates which we regard as the age of crystallisation of the TTG precursors.

Comparison of the palaeo-isochron with terrestrial Pb-isotope evolution lines shows that the gneissic precursors of these ca. 3.81 Ga TTG gneisses were not derived from the mantle. They require the existence of a terrestrial reservoir with a higher U/Pb ratio than mantle. Similar requirements for a high U/Pb source have been found for IGB BIF (1), IGB carbonate (2), and particularly IGB galenas (3; 4). Significantly, a single high µ source that separated from the mantle at ca. 4.3 Ga with a µ of ca. 10.5 provides a good fit too all these observations. We propose that this was not a mantle source but the Hadean basaltic crust, which in the absence of the subduction process encased the early Earth. Differentiation of the early high µ basaltic crust could have occurred in response to gravitational sinking of cold mantle material (5) or meteorite impact, and produced zircon-bearing magmatic rocks. The subchondritic Hf-isotope ratios of ≥3.8 Ga zircons support this model (6) provided that the redetermined 176Lu decay constant of (7) is correct. We propose that initiation of terrestrial subduction occurred at ca. 3.75 Ga, at which stage most of the Hadean basaltic shell (and its differentiation products) was recycled into the mantle, because of the lack of a stabilising mantle lithosphere. Therefore, the preservation of ≥3.8 Ga terrestrial rocks and minerals is not fortuitous, but reflects intrusion of voluminous granitoids immediately after establishment of global subduction because of complementary creation of a lithospheric keel.

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Kamber et al.

Terrestrial Nb/Ta evolution: New evidence from iron meteorites and early Archaean metabasalts s.l.

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The concept of primitive mantle or bulk silicate Earth is a cornerstone of geochemical interpretation. Bulk silicate Earth is a hypothetical undifferentiated silicate (mantle) reservoir that could have existed after formation of the core and establishment of the proto-atmosphere. The composition of bulk silicate Earth cannot be determined directly but must be estimated by subtracting the element inventory of the metallic core from an estimated bulk Earth with chondritic element distribution. For many elements, particularly those of refractory (i.e. non-volatile) and highly lithophile (i.e. excluded from the core) character, bulk-silicate Earth estimates are widely regarded to be robust.

Results of recent experimental studies (1) surprisingly suggested, however, that at greatly reduced oxygen fugacity and at great depth (several hundreds of km), conditions like those expected at the base of a hypothetical magma ocean, some elements (e.g., Nb and V) which are highly lithophile could nevertheless assume a siderophile character and hence be partitioned into the metallic melts that formed the core. More surprisingly still, the same study (1) also found that elements that are regarded to be chemically virtually identical (e.g. Nb and Ta) did not exhibit the same siderophile character. These proposals are serious news for estimates of bulk silicate Earth composition that all rely on the no longer safe assumption that lithophile elements were excluded from the core.

Here we propose that one way of testing experimental findings is to study the elements in question in the Earth's most ancient metabasaltic rocks. The rationale behind the approach is that if there ever existed a mantle source that closely resembled bulk silicate Earth, it could only have been early in Earth's history. Once a significant amount of continental crust was extracted from the mantle, depletion factors are very difficult to constrain. In this presentation we discuss, as a case study, terrestrial Nb-Ta systematics from the perspective of the Earth's oldest metabasalts, including examples from the Itsaq gneiss complex.

A Nb-Ta mass imbalance exists in the accessible Earth in that continental crust (Nb/Ta = 11), MORB (Nb/Ta = 16.7), OIB (Nb/Ta = 14-18), and lithospheric mantle xenoliths (Nb/Ta = 10-18) all have a lower Nb/Ta ratio than chondrites (17.4±0.5) (2). This undoubtedly requires a hidden reservoir with a high Nb/Ta ratio. Previous models (3, 4) identified that reservoir as subducted eclogite slabs that accumulated in the mantle transition zone or in the lower mantle. However, more recent experimental data showed that under appropriate conditions, Nb but not Ta can be siderophile, opening the possibility that the hidden Nb resides in the core. In an attempt to test this proposal, we determined Nb and Ta concentrations of iron meteorites. These are cores of early planetesimals that formed by relatively shallow metal melt segregation. Our ICP-MS Nb and Ta determinations showed that the metal phase of different classes of iron meteorites is devoid of both Nb and Ta. However, troilite inclusions of the iron meteorite Canon Diablo do contain appreciable amounts of Nb (350-500 ppb) but no Ta. This qualitative finding thus suggests that Nb could partition into the metallic melt from which it eventually could have been incorporated into the sulphide phase (i.e. it is strictly speaking chalcophile).

The amount of Nb that might reside in the Earth's core cannot, however, be estimated from iron meteorite data, because the metal/silicate partition coefficient strongly depends on depth and oxygen fugacity. In this context, we regard it as significant that three suites of 3.65-3.82 Ga metabasalts and basaltic metakomatiites (from the Itsaq gneiss complex, Northern Labrador, and Acasta) have Nb/Ta ratios significantly lower than chondrite. There is no discernible difference between the average ratios of the three units and an average Nb/Ta ratio of 15.11±1.86 can be calculated from all samples. Because the bulk distribution coefficients of Nb and Ta are indistinguishable in astenospheric melting, we regard a Nb/Ta ratio of 15.1 as representative of the early Archaean mantle. On the premise that the amount of low Nb/Ta continental crust was small, it can be calculated that ca. 13% of the terrestrial Nb is hidden in the core. This is much less than the amount predicted from experimental studies (23%) for metal/silicate fractionation at the bottom of a ca. 600 km deep magma ocean.

In our interpretation, the increase in Nb/Ta ratio in the MORB-source mantle from 15.1 to 16.7 reflects extraction of low Nb/Ta continental crust. Secular variation in MORB-source Nb/Ta ratio is observed and indicates that high Nb/Ta eclogite slabs only started accumulating in the deep mantle after 2.7 Ga. Implications for Archaean "plate" tectonics and continental growth will be discussed.

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Kamo et al.

Chronological and isotopic tracer data from intrusions south of the Isua supracrustal sequence and a report on a 3.9 Ga tonalite gneiss

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New, combined U-Pb and Lu-Hf data are reported on single zircon crystals from 5 tonalitic gneiss samples that were collected approximately 15 km south of the Isua supracrustal belt. This area exposes extensive, amphibolite-facies, tonalite-trondhjemite gneiss that Nutman et al. (1999) note has a greater proportion of homogeneous gneisses and low-strain, meta-tonalites than anywhere else in the Itsaq gneiss complex. U-Pb data were obtained by isotope dilution thermal ionization mass spectrometry (IDTIMS). Lu was determined by IDTIMS and Hf by ID-MC-ICPMS. Rb-Sr data from bulk zircon fractions containing inclusions of apatite or melt were also obtained.

One of the tonalite intrusions appears to be approximately 80-100 m.y. older than those reported previously in this area by Nutman et al. (1999) and Crowley and Myers (2001). The rock is a weakly deformed, homogeneous tonalite gneiss containing a dominant zircon population of oscillatory-zoned, euhedral to subhedral, prismatic crystals that give an upper intercept age of 3900±17 Ma. The oldest datum has a 207Pb/206Pb age of 3888.9+/-2.2 Ma and is 0.5% discordant. A subpopulation of smaller, unzoned zircons give ages of about 3816 Ma. Th/U ratios for these populations are 0.4 and 0.3, respectively. Initial Hf for the older population is the most primitive obtained in this study with 176Hf/177Hf=0.280262+/-

0.000008. Here, we prefer to report Hf isotopic data as initial ratios, rather than the more conventional εHf values. Initial ratios are almost independent of the Lu decay constant, which is currently being debated (Begemann et al., 2001).

Four other tonalite gneiss samples contain complex zircon populations that formed in at least two or more episodes. Sample SK00-1 has 5 data that give an upper intercept age of 3816+19/-13 Ma and 2 data that indicate an age of 3720 +/-9 Ma. Th/U in the older population ranges from 0.4-0.9 and is much lower in the younger population at 0.01 and 0.1. Etching in NaOH prior to selection and air abrasion appears to have improved concordancy. Initial Hf values for each age are distinct giving 0.280383+/-0.000016 for the younger 3.72 Ga zircons, and 0.280316+/-0.000007 for the older 3.82 Ga grains, thus indicating the presence of two distinct generations of zircon growth. SK00-4 is from Nutman et al.'s (1999) site 'B' and contains a homogeneous population of pale brown zircon that give an upper intercept age of 3808+/-10 Ma from 3 analyses, identical to that reported by Nutman et al. An additional near-concordant point has a 207Pb/206Pb age of 3602.1+/-1.4 Ma. One very large bulk fraction gives the older age and indicates that the younger population is a relatively minor component of the entire zircon population. Th/U is 0.3 in all single grains and the bulk fraction. Three of 4 data points have overlapping initial Hf ranging from 0.280328+/-0.000006 to 0.280335+/-0.000006, one analysis with the highest 207Pb/206Pb age gives 0.280317+/-0.000006 and suggests that there is a small inherited component in this grain. The younger grain has initial Hf similar to the older grains, suggesting that later zircon growth was from a partial melt from a low Lu/Hf rock at 3.6 Ga.

In sample SK00-5, located about 2.5 km west of Nutman et al.'s site B (SK00-4), the dominant zircon population gives an upper intercept age of ca. 3740 Ma. A single, older, near concordant analysis is 3790+/-3 Ma and is likely an inherited grain from a nearby older source. It has a higher Th/U of 0.6 (versus 0.2-0.3 for the other 5 analyses) and the initial Hf ratio of this grain is distinctly lower (0.280303+/-0.000006) than the 0.280392+/-0.000010 value obtained for the main population. SK00-11is from Nutman et al. (1999) site 'A' locality. The upper intercept age of 4 data, from 3 single grains and 1 large bulk fraction, is 3818± 58 Ma. A single grain has an older 207Pb/206Pb age of 3851+/-1 Ma (0.9% discordant) and the initial Hf value is markedly lower at 0.280294+/-0.000006 than the ratios obtained for the younger population (ranging from 0.280317+/-0.000007 to 0.280324+/-0.000007). Initial Hf for the bulk fraction is identical to that for 2 single grain analyses and supports the interpretation that the 3818 Ma age represents the time of tonalite crystallization.

Lower intercept ages for SK00-5 and SK00-11 indicate ancient Pb loss and/or minor amounts of new zircon growth at ca. 3.1 Ga, while those for the other 3 samples show late Archean (ca. 2700-2500 Ma) Pb loss, contemporaneous with titanite growth in the same rocks (Amelin, this volume).

Results from Rb-Sr analysis on large zircon fractions weighing between 0.1-0.6 mg give an initial 87Sr/86Sr value of 0.751+/-0.021 and an isochron age of 1735+/-490 that may indicate the time of latest isotopic disturbance in this area.

Lu-Hf isotopic data obtained from accurately dated single zircon crystals offers the enhanced opportunity of acquiring reliable isotopic information from closed geochemical systems, and thus reliable Hf isotope data on the earliest preserved rocks. Our overall Hf results, assuming the 176Lu decay constant is 1.93*10-11 , indicate an εHf range of +1 to +4, and mainly between +2 to +3, indicating that mantle source depletion occurred before 3.9 Ga. If we use the 176Lu decay constant of 1.86*10-11 the range of εHf shifts down by about three epsilon units so the range is –2 to +1. This would be interpreted as source derivation from an undifferentiated mantle, that was affected by an older crustal component. There is a general trend towards lower εHf with decreasing age in the εHf versus 207Pb/206Pb age plot, for either decay constant. This suggests an increasing role of crustal reworking during the latter part of the Isua area history (3.4-3.6 versus 3.7-3.9 Ga).
Our geochronological and Hf isotopic results emphasize the long, complex geological evolution of the gneiss complex south of the Isua greenstone belt, from 3.9 Ga until the late Archean. Detailed characterization of individual episodes in the geological history of the southern gneisses will require studies of co-existing multiple igneous phases and their constituent minerals with a combination of geochronological and isotopic tracer methods.

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Kramers

Thermal and isotope considerations on the growth and destruction of earliest continental crust

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It is now established that some continental crust existed about 4.35 Ga ago (Wilde et al., 2001). Important questions remain, such as: How much of it was there? How rapidly was it eroded and maybe recycled into the mantle?

There can be some doubt on thermal grounds about the mechanical stability of continental crust in very early times. The main long lived heat producing radioactive species 40K (half life ~1.3 Ga), 232Th (~14 Ga) 235U (~0.7 Ga) and 238U (~4.5 Ga) are among the incompatibles greatly enriched in the crust (about 100 × relative to bulk Earth). A normal granite producing about 1 μW/m3 today would have produced 3.7 μW/m3 at 4 Ga, and 4.6 μW/m3 at 4.4 Ga. Steady state geotherm calculations, even assuming low basal heat flow from the mantle, show that at 4.4 Ga continental crust of average composition and thickness (about 35 km) would have melted its own basal portion. A 20 km thick crust could however have been stable. As a thin crust would cause less topographic relief, destruction of crust by erosion is much less likely to have occurred in the Hadean than today.

Initial εNd and εHf values of of ancient crustal provinces have been brought to bear on the problem of how much continental crust existed very early in Earth's history, based on the idea that a large amount of early crust would have rapidly generated depleted mantle signatures. Apparent εNd indications for such early depleted mantle (e.g. Bowring & Housh, 1995) have been largely refuted as effects of later resetting of Sm-Nd systematics in metamorphic events (Moorbath et al.1997). εHf values of zircons, dated by U/Pb, provide a more robust indicator (Amelin et al., 1999) and indeed appeared to show some evidence of early depleted mantle (Amelin et al., 2000). However, the recalibration of the 176Lu decay constant (Scherer et al., 2001) has shifted the reference framework CHUR to more radiogenic values. Now the evidence for depleted mantle sources before 3.5 Ga disappears. On the other hand, a model age of c. 4.4 Ga is now derived for the Jack Hills population of Amelin et al. (2000), quite similar to the oldest U-Pb age obtained from this population (Wilde et al., 2001). The Jack Hills zircon population thus shows that some continental crust was generated at 4.4 Ga, and survived as a geochemical entity up to 3.8 Ga but obviously suffered frequent internal remelting, causing new zircons to crystallize. This behaviour, and similar observations on the (non-detrital) Acasta zircons, concurs with the above thermal considerations.

In attempts to constrain early continent erosion via global forward modeling of U-Th-Pb and Sm-Nd systematics in terrestrial reservoirs (Kramers & Tolstikhin, 1997; Nägler & Kramers, 1998) no fits to present day data were obtained with scenarios n which a large amount of crust existed early in the Earth's history. The reason is that the large amount of crust to mantle recycling required by these makes it impossible to reproduce the isotope differences observed today between continental crust and upper mantle. The best fits were obtained with scenarios in which no continental crust existed until 4 Ga ago. Rapid growth then produced a continental crust about 70% of its present day mass by 2 Ga, and was followed by slower net growth. These results are in agreement with crustal histories obtained from age distribution and sediment geochemistry considerations (Taylor & McLennan, 1995) and from Th-U-Nb systematics of the mantle (Collerson & Kamber, 1999). They are in apparent contradiction with the Jack Hills zircon εHf results. However, the global modeling has too poor a resolution to "see" an amount of very early continental crust less than a few % of the present crust mass. Further modeling (Kramers, in Press) has focused on the rate of crust-to.mantle recycling in the Archean. It has yielded the result that the rate of crust to mantle recycling per unit of continent area (related to the erosion rate) was certainly not greater in the Archean than it is at present. If the erosion rate is set constant over time, a value of c. 10 mm/kyr is obtained.

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Kramers

Some thoughts on the very early history of Earth's atmosphere: Wholesale loss, H_2O retention and CO_2 drawdown

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The geological history and climate of the Earth during its first 600 million years are largely unknown, which hampers our understanding of Archean atmosphere development and climate conditions. Nevertheless reasonable confidence exists about a number of parameters that limit the scope for speculation or could even constrain climate models for the early Earth.

The volatile elements H, C and N are heavily concentrated in the surface reservoirs of the Earth (Atmo-hydrosphere, sediments and metasediments), although significant C and H might also reside in the Earth's core. Apart form the unknown core-component, the terrestrial budget of these gases is depleted by a factor ~10-3 compared to carbonaceous chondrites, and by between 10-8 (H) and 10-5 (C and N) relative to solar abundances (when normalized to refractory elements). The terrestrial budget of halogens, also concentrated in the surface reservoirs, is much less depleted (~10-2 × c.chond. or solar alike), while the noble gases are more strongly depleted (~10-11 for Ne, to ~10-6 for Kr and Xe × solar). For the latter, a strong depletion relative to solar abundances (10-8 to 10-3) already exists in carbonaceous chondrites. The terrestrial relative abundance patterns for C, N and the halogens are very chondrite-similar, whereas those for the noble gases must originally have been solar-similar (e.g. Tolstikhin & Marty, 1998). If it is assumed that the Earth obtained all its matter from globally chondritic accretion, this is an apparent contradiction. It can be resolved if a small fraction (a fraction between 10-6 and 10-5 of accreting matter) of solar nebular atmosphere or implanted solar wind is assumed to be incorporated in the Earth.

The carbonaceous chondrite-normalized H/C and H/N ratios of the Earth's surface reservoirs (and also of the silicate Earth as a whole) are ~10 and ~5, respectively. If a 10-5 solar component for terrestrial volatiles is assumed, this overabundance still remains. The hypothesis that comets made a very significant contribution to the Earth's water budget over time is prohibited by the observation that cometary D/H isotope ratios are twice the terrestrial value (Balsiger et al., 1995). A further strong case is made by comparing the terrestrial H/C ratio (~50 molar) with that of comets (~ 7). Therefore the volatile element abundance pattern of the Earth's surface reservoirs is very ancient, and likely to be determined much more by differential loss of the different elements, than by specific addition of some.

The primordial atmosphere must have been largely accumulated by degassing (impact-related as well as volcanic), and its almost complete loss could have been caused both by catastrophic impacts and/or by hydrodynamic escape, driven by a thermal H (and to a less extent He) flux from the outer atmosphere. The isotopic fractionation of terrestrial Kr and Xe relative to chondrites (with light isotopes being more depleted) indicates that the second process was important (Pepin, 1997). The necessary H is provided by UV photolysis of H_2O or CH_4; a disproportionate early H loss is implied, which again aggravates the initial terrestrial H overabundance problem. From 129Xe(I)-136Xe(Pu) systematics it can be concluded that outgassing of the solid Earth and loss of the atmosphere, by whichever mechanism, must essentially have occurred within the first 200 m.yrs of Earth history (Azbel & Tolstikhin, 1993). Degassing of the trace noble gases can only have occurred together with major volatiles (H_2O, CO_2, CO, CH_4, N_2). Therefore we know that outgassing of terrestrial H, C and N into the atmosphere (and their extensive loss) must also have occurred in the first 200 m. yrs. The Xe fractionation indicates that a significant part of the present atmosphere is a remnant of loss, rather than the product of later degassing. Therefore the present H, C and N budget of the Earth's surface reservoirs was largely already present in these reservoirs at 4.35 Ga.

A working hypothesis is presented following which a large proportion of H_2O was present as liquid water and/or ice at the time of main atmosphere loss. This would have caused the loss of H from the Earth's surface reservoirs to be underproportional to its total abundance in these reservoirs. It would also help to explain the relatively minor terrestrial depletion of the halogens Cl, Br and I, which can form strongly water soluble compounds. The hypothesis concurs with O isotope evidence from >4.3 Ga detrital zircons (Wilde et al., 2001).

The Earth's post-loss atmosphere must still have been very dense. The amount of C presently in sedimentary and metasedimentary rocks is 3.6 $\times$ 1021 moles (Wedepohl, 1995). If all present as CO_2 this would form a ~30 bar atmosphere, and as CO, ~19 bar. Over the age span of the solar system, the radiance of the sun has increased steadily from an initial value about 70% of its present one. For the early Archean, the (interpolated) 20% fainter solar irradiation compared to today requires a greenhouse effect, as exogenic processes driven by liquid water are abundantly observed in rock units that predate the earliest evidence of glaciation (in the ~ 2.9 Ga Mozaan Group, South Africa, Young et al. 1998). The dense atmosphere could have produced an adequate greenhouse effect preventing our planet from freezing at 4.4. Ga (Kasting & Ackermann, 1986). Although these authors' modeling predicts Earth surface temperatures of ~100° C for a ~30 bar atmosphere at that time, the elevated boiling point would prevent boiling away of the oceans. This still applies if C occurred chiefly as CO or CH4.

Carbon isotope data show unequivocally that ~80% of Earth surface C is present in carbonate form, and ~20% as organogenic matter, and that this has been so throughout known geological history (Schidlowski, 1988). This means that silicate weathering, followed by carbonate precipitation, has been the most important process to achieve carbon fixation, about 4 × more important than biological photoautotrophy. Removal of CO_2 led to the Mozaan Glaciation at 2.9 Ga and then the widespread Huronian glaciation (Nesbitt & Young, 1982) in spite of increasing solar luminosity. The removal of C from the atmosphere by silicate weathering and carbonate formation requires that it is present as CO_2. It further requires rain, rivers, a sea, and erosion to remove weathered cover and expose fresh silicates.

Evidence that intense chemical weathering occurred in the Archean and early Proterozoic is provided by marked depletions in Na, K and Ca in paleosols when compared to the corresponding unaltered rock (Rainbird et al. 1990) and also in Archean shales and metapelites compared to average upper continental crust (e.g. Nesbitt & Young 1982, Fedo et al. 1996). In these studies, the immobile trace and major element geochemistry of the metasediments indicates provenance from ordinary Archean granitoid crust, so that the mobile element depletion can be attributed with some confidence to chemical weathering in the source area. This evidence of Archean chemical weathering, in accord with the occurrence of carbonate rocks in the Archean, bears witness to CO_2 drawdown. Continents are a prime location for the weathering process as they stay above sea level for a long time. Therefore if Archean continental weathering could be quantified, it could at least yield a minimum estimate of early CO_2 drawdown potential.

Time-integrating the Archean crust recycling rates obtained from modeling (Kramers, 2001) and translating the result into cumulative CO_2 drawdown capacity shows that excess CO_2 could have been drawn down from the atmosphere by c. 2.6 Ga at the earliest. This is in conflict with the evidence of glaciation in the 2.9 Ga Mozaan Group (Young et al., 1998). Clearly there are other possible settings: Weathering could have occurred even during accretion (Nisbet & Sleep, 2001) but this is irrelevant for Archean climates as it preceded or occurred during major atmosphere loss. Volcanic islands or the Hadean/Archean equivalent of mid ocean ridges could weather, if they emerged from the sea.

If the assumption is made that this recycling is a measure of erosion, and that erosion in turn is a measure of chemical weathering, the results of modeling allow to place constraints on the potential for early CO_2 drawdown.

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Lepland et al.

Apatite in early Archean Isua supracrustal rocks, southern West Greenland: Its origin, association with graphite and potential as a biomarker

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Rare earth element (REE) abundances in individual apatite crystals in banded iron formations (BIFs), metacherts, metacarbonates and mafic dykes in the Isua supracrustal belt (ISB) have been determined by laser ablation inductively coupled plasma mass spectrometry. The results together with petrographic observations on the distribution of graphite have been used to track the origin of the different compositional types of apatite and to evaluate the potential, proposed in earlier studies, for use of the apatite-graphite association as a biomarker.

The chondrite-normalized distribution patterns of apatite in metasedimentary BIFs and metacherts fall into three groups. Relatively flat profiles with distinct positive Eu anomaly are interpreted as characterizing sedimentary (diagenetic) apatite that carry the REE signature of the Archean ocean. Secondary apatite in Isua metasdiments with either middle REE enriched profiles or with light REE depleted profiles is thought to have crystallized from percolating carbonate-rich metasomatic fluids or from fluids derived from cross-cutting mafic dykes, respectively. The occurrence together of these different genetic types of apatite with distinct REE signatures within cm-scale samples shows the immobility of REE in preexisting apatite during metamorphic episodes.

Apatite crystals in Isua metasedimentary rocks (BIF and metachert samples) do not have graphite inclusions or coatings. Graphite inclusions and coatings on the other hand characterize apatite in secondary metacarbonate rocks. In these rocks graphite is produced by thermal-metamorphic reduction of carbonate ion, derived from dissociation of the metasomatic ferrous carbonate while iron serves as electron acceptor, oxidizing to form magnetite. In view of the non-sedimentary, metasomatic origin of Isua metacarbonates and the abiogenic source of graphite, the apatite-graphite assemblage can not be considered as a biomarker and does not provide information on early Archean life in the ISB.

Lowry et al.

Oxygen isotopes of an early Archaean layered ultramafic body: implications for magma source and post-intrusion history

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Minerals separated from the Ujarargssuit Nunat layered body have been analysed for d18O by laser fluorination. The ranges obtained from dunite and harzburgite are: olivine 4.54-4.80‰, orthopyroxene 5.73-5.81‰, clinopyroxene 5.44-5.59‰ and chrome-spinel –0.13-0.51‰. A banded chromitite has coarse olivine with d18O of 4.71‰ but chrome-spinel at 1.75‰. The intrusion has been subjected to high-grade metamorphism, but for the most part the primary mineralogy remains intact.

Oxygen isotope thermometry is largely dependent on mineral phases crystallising in equilibrium with each other, but also relies on their having been no diffusion of oxygen during metamorphism. Studies of other layered intrusions suggest that olivine is least affected by post-crystallisation events and will have a signature close to the primary magmatic values. The values recorded in the Rum and Skye layered series of the British Tertiary Igneous Province, also have olivine d18O in the range 4.3 to 4.8‰. In the Rum intrusion late meteoric water input into the chamber has had the effect of lowering clinopyroxene d18O, but there is no evidence for this at Ujarargssuit Nunat. Temperatures recorded for mineral pairs vary from 500-830°C, but the most reliable and intimately related mineral pair is chrome-spinel and clinopyroxene. These record temperatures of 570-640°C, similar to the range suggested by olivine-spinel mineral chemistry, but much lower than the 980-1120°C suggested by these mineral pairs for the Rum intrusion. Widespread re-equilibration during metamorphism involving chrome-spinel should result in a decrease in d18O of the other phases but so far there is little evidence for this.

Analysis of amphibole and plagioclase from the upper parts of the intrusion are required to shed further light on the post-crystallisation and metamorphic history. So far the main silicate minerals give d18O values typical of layered series and mantle-derived magmas.

Moorbath

Where do we stand with Isua research?

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Highly conflicting geological interpretations of the Isua greenstone belt (IGB) have been published in recent years. At one extreme, it has been implied that intense deformation, metamorphism and metasomatism (abbreviated here to DMM) have transformed all or most of the rocks to such a degree that they now represent no more than a pale, ghostly relic of their protoliths, enabling only the most tenuous identification to be made between rocks and protoliths, and then only in isolated instances. At the other extreme, some workers claim that the preservation of primary depositional features from the protolith is fully adequate to enable detailed stratigraphic and structural mapping of exposed IGB rocks and, hence, to make close comparison with Phanerozoic oceanic plate stratigraphy, etc. (1)

The truth seems to lie somewhere in-between. Exactly where in the spectrum of possibilities it lies depends on the specific lithology of a given rock and of the intensity of DMM which it has undergone. In some cases, protolith features are easily identifiable in the field whilst, in others, sophisticated metamorphic and geochemical studies are essential. Two plausible reasons for many conflicting interpretations in the IGB are that (i) few geologists have sufficient personal field experience of such a complex suite of ancient rocks with such a high (though variable) degree of DMM, (ii) different sectors of the IGB (e.g. east and west, broadly speaking) exhibit different proportions of rock types and intensity of DMM, so that workers familiar with one area have tended to make generalisations about the whole IGB which are simply not regionally valid. One of the main reasons for setting up the Isua Multidisciplinary Research Project (IMRP) was to enable workers from a wide range of experience and disciplines to tackle a broad range of stratigraphic, tectonic, metamorphic and geochemical problems based on the best available field evidence, and to produce a new, more accurate geological map of the entire IGB and adjacent areas.

It has been known for thirty years (2) that IGB rocks are at least ca. 3.7 Ga old. This has not changed much, but there is some controversy whether deposition (and, possibly, their first metamorphism) occurred closer to 3.7 or to 3.8 Ga. This depends on the rock type, on the isotopic method used, and on the interpretation of field evidence. There may even be two major components of the IGB, differing in age by ca.100 Ma. No direct age evidence for rocks >3.81 Ga has been reported, but recent Pb-isotope data on IGB metasediments and Pb-ores (3) suggest that certain geochemical features pertaining to pre-4.0 Ga mantle and crust can be recognised. Other radiogenic isotope data on IGB rocks (e.g. Nd, Hf) must be interpreted with extreme care on account of DMM open system behaviour, but tentatively suggest that the mantle source region of IGB rocks and adjacent early Archaean granitoids was slightly depleted, or bordering on chondritic, thus not allowing for pre-3.8 Ga mantle-to-crust differentiation on a grand scale.

Within the circular outcrop of the IGB, there are granitoid orthogneisses reliably dated at ca. 3.65-3.70 Ga. A large area (ca. 1000 km^2) south of the IGB comprises granitoid orthogneisses with abundant enclaves of varied mafic and ultramafic rocks, as well as chemical sediments such as banded iron formation (BIF). In places, deformation is remarkably low, and some zircon U-Pb dates of ca. 3.8 Ga have been reported from the gneisses (4). Part of the area had already been mapped by 1981 by Brian Chadwick (maps held by GEUS, Copenhagen), with very plausible geological interpretations. This southern gneiss terrain is currently being mapped by Jim Crowley, John Myers and colleagues, including the contact with the IGB to the north. Clearly one of the main regional aims is to use detailed field and geochronological data to understand the tectonic nature of the intercalation of the IGB between two gneiss terrains of possibly different early Archaean ages.

If these gneisses to the south of the IGB are really ca. 3.8 Ga, then their enclaves are clearly older, and could even turn out to be older than some similar rocks from the IGB, depending on the real age(s) of the latter (i.e. whether 3.7 or 3.8 Ga). This may be an exciting area for further research into the oldest rocks.

No evidence for lunar-type (or any) meteoritic impact has yet been reported for IGB rocks, though several workers appear to be searching. Recent work (5) supports the concept of a short, intense period of bombardment in the Earth-Moon system at ca. 3.9 Ga. This is at least 0.1 Ga older than deposition of IGB rocks, by which time impact frequency was declining rapidly. This may account for the absence so far of any observed impact effect.

Possibly biogenic carbon particles have been reported (6) from a locality of deformed, metamorphosed sediments in the western part of the IGB. The problem is to decide whether the diagnostic C-isotope fractionations are truly biogenic, or could have been produced by non-biological processes. The analogous, much publicised situation on Akilia Island, some 150km southwest of Isua, is even more problematic because there the petrological identification of the carbon-bearing rocks, the nature of their field relationships with the adjacent, dated granitoid gneisses, as well as the interpretation of the ages themselves, all pose severe uncertainties for deciding whether life already existed by 3.8 Ga (7). At any rate, in principle, life could have started, or re-started, soon after globally sterilising impacts at ca. 3.9 Ga (8).

Debate continues on the depositional environment of IGB rocks. Voluminous pillow basalt, BIF and chert testify to a none-too-shallow marine environment. (Primary carbonate deposition in the IGB is now regarded by most workers as minor or absent). Locally there are relatively minor horizons regarded by some as true pebble (mainly chert) conglomerates, by others as tectonised pseudo-conglomerates derived mainly from chert horizons. The former interpretation implies the existence of some kind of land mass. Putative conglomerates do not contain clasts of granitoid gneiss. Curiously neglected in recent descriptive fieldwork are the voluminous, spectacular horizons of massive garnet-mica-plagioclase-quartz (±amphibole, ±staurolite) etc. schists, which contrast strongly with adjacent metabasalts. These rocks might have been pelitic in origin (9), with mafic, volcanogenic sediments as protolith. Such rocks could imply shallow water deposition, with derivation from a volcanic landmass. Much more work is needed on these rocks. Also present in the IGB are several types of problematic, fine-grained high-silica rocks, some of which have been tentatively identified as felsic, volcanogenic metasediments, and others as highly deformed and metsomatised intercalations of granitoid orthogneiss within the IGB.

The IGB and nearby related rocks arguably represent the closest possible approach to the time of putative, massive global impact at around 3.9 Ga, after which total restructuring and renewal of the earth's surface occurred within a period not exceeding ca. 100 Ma. Furthermore, the adjacent granitoid orthogneiss terrains probably represent some of the earliest true continental crust, formed by petrogenetic and tectonic mechanisms not unlike those of later periods. This unique regional package of in-situ rocks deserves much further study, because it represents a period in earth history when geological processes as we know them became recognisable and when conditions for life became favourable.

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Mudrovska & Appel

The origin of hematite ore in the Isua iron formation, West Greenland

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The 3.75 Ga Isua Greenstone Belt (**IGB**) in West Greenland hosts different facies of iron formation. Banded iron formation (**BIF**) consists of oxide- with minor silicate- and sulphide facies. In the northeastern part of the **IGB** a world class iron deposit with ~2 billion tonnes of magnetite-quartz banded ore is seen. On top of the magnetite-quartz banded ore body a large hematite ore body occurs.

The IGB comprises extensive mafic pillow lavas, intrusive mafic and ultramafic rocks, cherts and banded iron formation (**BIF**). Minor quartzo-feldspathic schists may represent felsic volcanic rocks. Persistent garnet biotite schists together with polymictic conglomerates represent sedimentary intercalations in the greenstone belt. The **IGB** is hosted in and intruded by tonalites. The greenstone belt has suffered several phases of intense deformation and metasomatism, and has been repeatedly metamorphosed up to amphibolite facies conditions at 3.65 – 3.70 Ga and at 2.8 Ga.

Oxide facies iron formation consist of alternating up to 30-cm thick magnetite-rich and quartz-rich bands (**BMQ**). **BMQ** are severely deformed and consist of intercalated iron-rich and silica-rich bands. The iron-rich bands are mostly fine-grained and composed of a magnetite-quartz mosaic aggregate with 10-20 μm sub- to anhedral grains. The margins between quartz and magnetite are sharp; quartz includes tiny grains of magnetite. No growth zonation, hematite exsolutions, or hematite relicts in magnetite have been observed. Silica-rich bands of **BMQ** consist of fine-grained quartz with minor magnetite, sulphides and grunerite. Chlorite and carbonate replace silicates and are seen in cross-cutting veins. Mineral orientation parallel to banding in fold limbs and normal to banding in fold closures is testifying syndeformational **BMQ** origin. It can reasonably be assumed, that **BMQ** formed jointly with Isua supracrustals and was deformed, metasomatised and metamorphosed to under amphibolite facies conditions.

Banded hematite-quartz ores (**BHQ**) have the same texture as **BMQ**, but have been subjected to brittle deformation. Near surface levels **BHQ** are brecciated and cemented by fine-grained quartz and carbonates. The rock porosity in **BHQ** is higher than in **BMQ**, and increases towards the surface. The iron-rich bands of **BHQ** are composed of hematite and quartz with varying amounts of magnetite and sulphides. Magnetite is often broken, but hematite, which envelopes the fractured magnetite, is undeformed. Hematite also forms a network of criss-crossing lamellae in magnetite, martitic rims around magnetite. Corroded magnetite is preserved in pyrite-markasite aggregates, hematite and goethite. Goethite develops only near the surface; it replaces magnetite, sulphides and hematite. Silica-rich bands of **BHQ** consist of quartz with subsidiary amphiboles, chlorites. Hematite forms 0.5-3 mm lath-shaped grains normal to the contact of iron- and silica bands, or fills the intragranular space in quartz aggregates, cleavage planes in amphiboles and chlorites. Hematite has grown in cavities in cauliflower structures (Fig. 1).

There are a number of evidences showing that **BHQ** formed after metamorphism, metasomatism and deformations of the Isua greenstone belt by progressive oxidation of **BMQ**:

1. Hematite formation is confined to areas with brittle fractionation. The transition from **BMQ** in lower part of section to **BHQ** on the upper horizons is observed.

2. The hematite develops along penetrating zones, such as contacts between iron- and silica bands, fractures, foliation planes, and intragranular space. Hematite content in-

creased from 0-1 vol.% from undeformed **BMQ** to 70-95 vol.% in highly deformed **BHQ**.

3. All textural features show that hematite formed by replacement of pre-existing magnetite.

4. Corroded magnetite relicts in hematite; hematite overgrowth of amphiboles, chlorites and recrystallised quartz indicate that the hematite developed after late metasomatic alteration (silicification, chloritization). Relicts of broken magnetite in undeformed hematite show the hematite development after brittle deformations of **BMQ**.

5. Hematite formation after Fe-chlorite, markasite, and stability of goethite in **BHQ** demonstrate the low-temperature (<100oC) mode of solutions. Quartz dissolution testifies the high pH and low salinity of solutions. Meteoric waters meet these conditions.

BMQ formed contemporaneously with Isua supracrustals and were deformed, metasomatised and metamorphosed under amphibolite facies conditions. After metamorphism and ductile deformations **BMQ** were subjected of brittle deformation. After last deformational event the million-year term of weathering and penetration of meteoric waters, which spread down along penetrative zones took place. The circulation of low-temperature alkaline fluids with high oxidation potential along high penetrative zones caused magnetite oxidation, silica dissolution and redeposition and as a result formation of hematite-quartz banded ores at the upper part of magnetite ore body.

I front of the inland ice covering the hematite ore body abundant loose blocks of silcreete are found. This indicate that the pre-Quarternary peneplain was not much above the present level of the hematite ore body. This lends further support to the suggestion that hematite wa

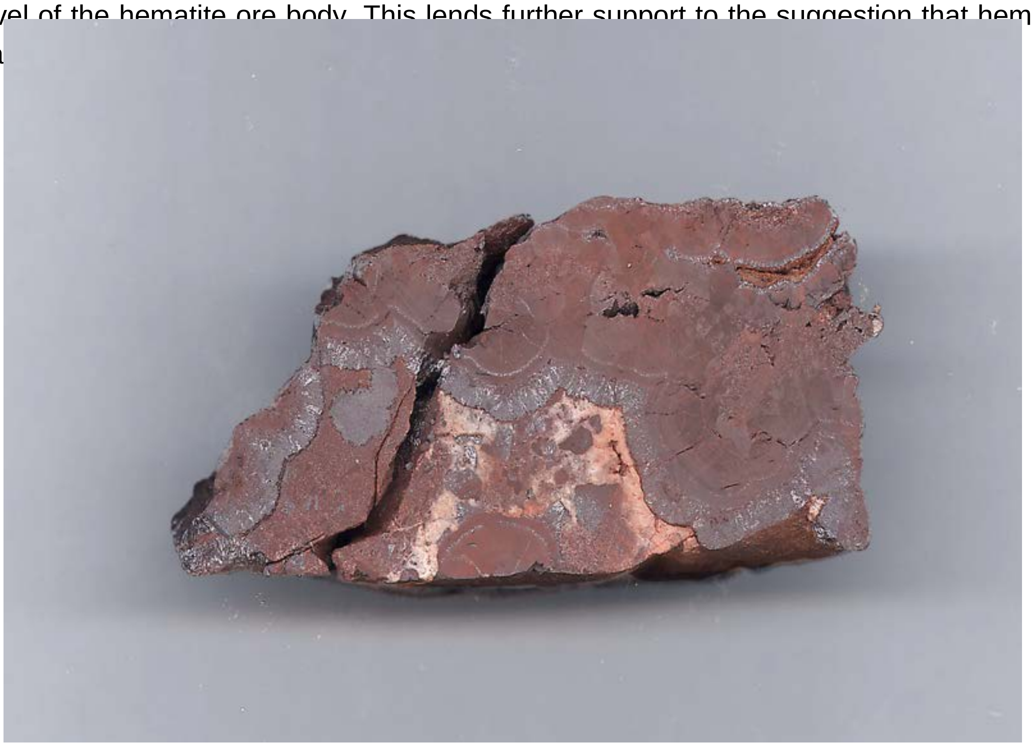

Fig. 1: Hematite-jasper cauliflowers grown in cavity.

Nielsen et al.

Petrogenesis of an early Archean (3.4 Ga) norite dike, Isua, West Greenland: Evidence for early Archean crustal recycling.

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An unaltered norite cumulate dike from the central part of the Isua area, West Greenland, has been studied in an attempt to determine the isotopic composition of early Archean mantle. A mineral (plagioclase-orthopyroxene) and whole rock Sm-Nd isochron yields an age of 3420 ± 60 Ma (MSWD = 1.9) and an initial Nd of -1.3. The mineralogy (opx+plag+ol+cr-sp) and mineral chemistry of the dike (opx: En90-70, plag: An73-54, ol: Fo90-87, and Cr-sp: Cr66-56), are consistent with crystallization from a near primary melt. However, a strong crustal signature characterizes the trace element and isotopic composition of the dike i.e. (Nb/La)PM = 0.20-0.25; Nd = -1.3 ± 1; (La/Yb)N = 4.8-4.1.

A series of hydrothermally altered samples up to 5 cm from a cross-cutting quartz-vein were analysed for trace elements and Nd isotopic composition in order to investigate the effects of post-crystallization alteration and metamorphism. These samples exhibit systematic changes in trace element and isotopic composition approaching the quartz vein (a total variation of ~2.5 Nd-units; (La/Yb)N = 5.5-4.1). The samples are more disturbed closer to the quartz-vein and have significant positive Nd values reflecting either metasomatic enrichment in the LREE or the addition of material with a positive Nd-value. This illustrates the dangers of using early Archean whole rock analyses to constrain the initial isotopic ratios of the Earth's earliest lithosphere.

In order to produce the trace element and isotopic signature of the dike, two potential processes have been modelled: (1) assimilation of crustal material by a primitive magma, and; (2) introduction of crustal material into a mantle source as might take place during subduction. Both trace element and isotopic models require unrealistically large amounts (>30%) of crustal assimilation, whereas the trace element and isotopic signature of the dike can be achieved by introduction of smaller amounts (< 5%) of crustal material directly into a mantle reservoir prior to melting. Therefore, we prefer a petrogenetic model for the dike involving early Archean subduction-related processes.

Polat & Hofmann

Diverse Geochemical Patterns in the 3.7-3.8 Ga Isua Greenstone Belt Volcanic Rocks

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A. Alteration of Pillow Basalts in the North Western and Central Tectonic Domains

Pillow basalts from the North Western and Central Tectonic Domains of the early Archean (3.7-3.8 Ga) Isua greenstone belt, West Greenland, are characterized by well-preserved rims and concentric core structures. The pillow rims and cores have different mineral assemblages, and chemical and isotopic compositions. The rims are characterized predominantly by hornblende + biotite + quartz + epidote, whereas the cores are composed primarily of hornblende + quartz + plagioclase calcite + epidote ± biotite ± chlorite. The rims have systematically higher contents of Fe2O3, MgO, MnO, K2O, Rb, Ba, Ga, Y and transition metals. In contrast, the cores possess higher concentrations of SiO2, Na2O, P2O5, Sr, Nb, and LREE. Collectively, these compositional variations in the rims and cores are likely to reflect the mobility of these elements during post-eruption alteration. Al2O3, TiO2, Th, Zr, and HREE display similar values in both cores and rims, suggesting that these elements were relatively immobile during post-emplacement alteration. In addition, the rims and cores have distinctive Sm-Nd and Rb-Sr isotopic compositions, in that the rims are characterized by higher 143Nd/144Nd and 87Sr/86Sr ratios than the cores, consistent with higher Sm/Nd and Rb/Sr ratios in the rims. The pillow basalts yield 2569±170 Ma and 1604±170 Ma errorchron ages on 143Nd/144Nd vs 147Nd/144Nd and 86Sr/87Sr vs 87Rb/86Sr diagrams, respectively. The Sm-Nd errorchron age may correspond, within errors, to the late Archean tectonothermal metamorphic event recorded in the region. Although, the Rb-Sr errorchron age overlaps with the timing of early to mid Proterozoic tectonothermal metamorphic event recorded in the Isua region, because of considerably large scatter in 86Sr/87Sr and 87Rb/86Srreatios, this age may not have a geological significance. Collectively, the Sm-Nd and Rb-Sr data obtained from the 3.7-3.8 Ga Isua pillow basalt rims and cores are consistent with disturbance of the Sm-Nd and Rb-Sr system by tectonothermal metamorphic events long after their eruption. Accordingly, the initial 143Nd/144Nd and 87Sr/86Sr ratios and their corresponding eNd and eSr values, calculated for the 3.75 Ga stratigraphic age of pillow basalt, are apparent rather than real. Fractionation of many elements (e.g.. Fe, Mn, Mg, Si, Na, Rb, K, Sr, Pb, Ni, V, Nb) between the rims and cores may have taken place during the early,Archean sea-floor hydrothermal alteration, whereas LREE were primarily fractionated during the late Archean metamorphic events. Collectively, the principal conclusions and implications of this study are: (1) primary volcanic textures and structures in the early Archean Isua pillow basalts played an important role in the generation of distinct post-magmatic changes in mineralogical, chemical, and isotopic compositions; (2) tectonothermal processes in the Isua region have resulted in the resetting of the Sm-Nd and Rb-Sr systems; and (3) the chemical effects of sea-floor alteration, as well as regional metamorphism, can be recognized.

Boninitic Signatures in the Central Tectonic Domain

The 3.7-3.8 Ga old Isua greenstone belt of southwest Greenland is characterized by variably metamorphosed, metasomatised, and deformed lithotectonic successions of volcanic and sedimentary rocks. The voluminous, mafic volcanic rocks are composed primarily of pillow basalts intercalated with ultramafic units. The sedimentary rocks consist mainly of banded iron formation, cherts, conglomerates, and siliciclastic turbidites. The least altered metavolcanic amphibolites (the Garbenschiefer unit) from the Central Tectonic Domain of the Isua greenstone belt are characterized by high Mg-number (0.60-0.80), MgO (7-18 wt.%), Al2O3 (14-20 wt.%), Ni (60-645 ppm), and Cr (60-1920 ppm) contents, but low TiO2 (0.20-0.40 wt.%), Zr (12-30 ppm), Y (6-14 ppm), and REE concentrations. These compositional features collectively represent a coherent mafic to ultramafic suite. Chondrite-normalized REE patterns are concave upward. On primitive mantle-normalized, extended trace element diaagrams, they are characterize by relative depletion of Nb, but enrichment of Zr, relative to neighboring REEs. Alteration, deformation, and crustal contamination can be ruled out as the cause of the distinct and coherent composition. The average initial eNd value of these metavolcanic rocks is +2. Collectively, these geochemical characteristics are comparable to those of Phanerozoic boninites. Given the observation that, in the Tertiary, boninites are exclusively associated with intra-oceanic subduction environments (e.g., Izu-Bonin-Mariana subduction system), this suggests that intra-oceanic subduction zone-like geodynamic processes were operating as early as 3.7-3.8 Ga ago.

The first proper pillow structures found at Isua.
They were discovered by Toshiaki Masuda

Rasmussen

Aeromagnetic data from Isua - implications on the structural interpretation

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High quality magnetic data from the Isua Area are available from two airborne surveys flown in 1998. GEUS carried out a regional survey that covers the entire coastal region and a small part of the permanent Ice Cap. Nunaoil A/S carried out a detailed survey of the Isua Area.

The data from the two surveys are presented together with a number of models that are derived from the data. The models are calculated by using three different geophysical modelling techniques:

- Modelling based on the analytical signal and various filtering techniques
- Forward modelling
- Inverse modelling

The models are discussed in relations to other structural information from Isua. The forward modelling involves a tentative kinematic description of structures in the Isua Greenstone Belt.

Rollinson

The Metamorphic History of the Isua Greenstone Belt, West Greenland

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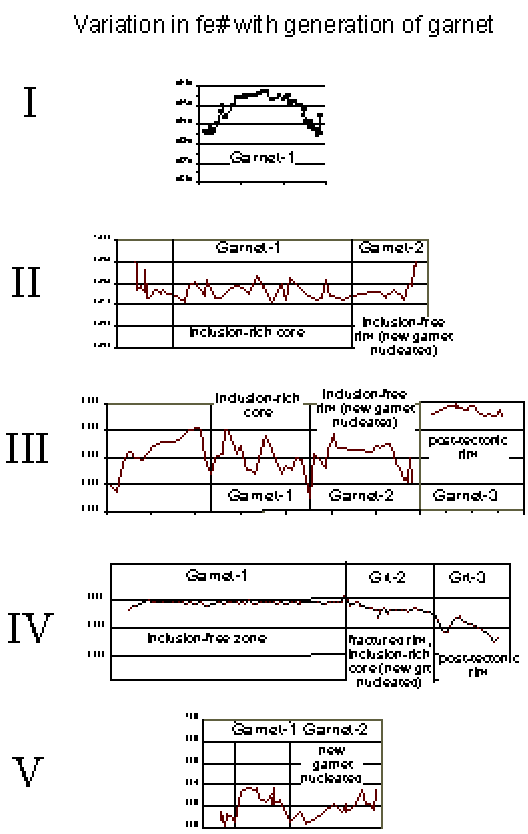
New geological investigations in the ca. 3.7-3.8 Ga Isua Greenstone Belt in west Greenland have revealed that the belt comprises a number of separate structural domains. Five such domains have been identified on the basis of lithological and structural differences. This study uses the morphology and compositional zoning of garnet pophyroblasts in pelites to investigate the extent to which the different domains within of the greenstone belt preserve contrasting deformational and metamorphic histories.



Up to three episodes of garnet growth have been identified in a single domain and significant differences in garnet growth history are noted between domains. A distinction is drawn between the relatively simple metamorphic history of a low strain zone in the northeast of the greenstone belt and other domains where more complex histories are preserved. Combining this result with existing geochronology suggests that in the south and west, the greenstone belt was metamorphosed twice at ca 3.74 Ga and again at ca 2.8 Ga, whereas in the northeast there was a single event at 3.69 Ga.

Preliminary garnet-rim thermometry, indicates that some rocks experienced an early metamorphism in which temperatures exceeded 610 oC. Kyanite is thought to have been in equilibrium with these assemblages, indicating pressures of at least 6 kb. A later prograde metamorphic event shows a temperature increase from 480 oC to 550 oC. The high pressures indicate a crustal thickness of at least 20 km at 3.7 Ga.

The geodynamic implications of these results will be discussed along with their relevance to recent carbon isotope studies for the Isua Greenstone Belt.

Rollinson et al.

A Metamorphosed, Early Archaean Chromitite from West Greenland: implications for the genesis of Archaean anorthositic chromitites

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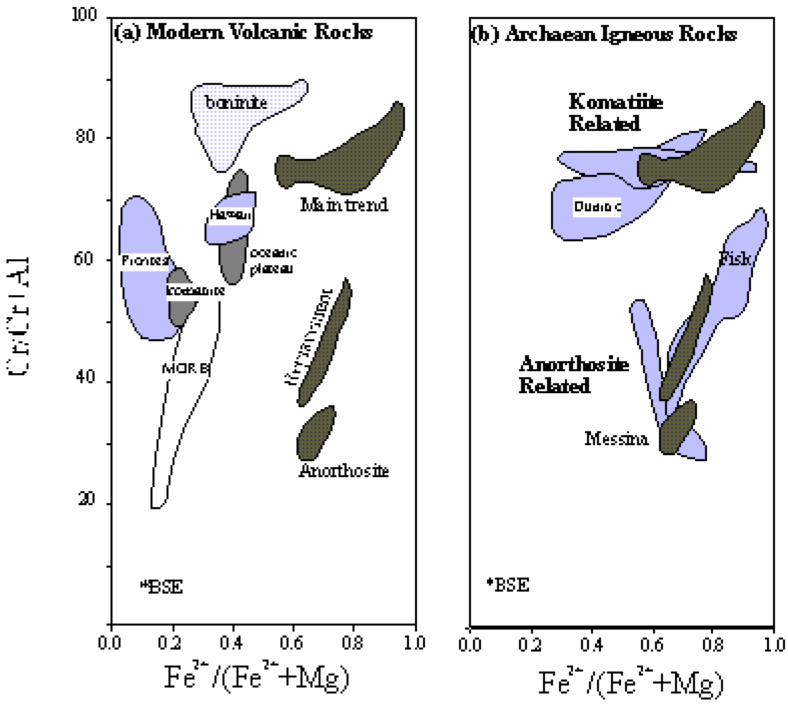
An early Archaean chromitite-ultramafic layered body from the Ujaragssuit nunât area, west Greenland is > 3.81 Ga old, and may represent the Earth's oldest chromitite. The layered body occurs as a large xenolith in tonalitic gneisses, preserves primary igneous layering and textures and is thought to have formed from a basaltic parent liquid. It has been metamorphosed twice, in the early and late Archaean.



Mineral chemistry and textures show that chromite compositions preserve two different evolutionary trends. There is a main magmatic trend in which Cr/(Cr+Al) ratios remain relatively constant but in which there is strong enrichment in Fe^{3+}, Fe^{2+} and Ti. This trend is a composite of magmatic-liquidus, magmatic-cooling and subsolidus equilibration processes. A second trend is defined by chromites from harzburgites in the upper part of the layered body. These chromites show magmatic replacement textures in which Fe-rich chromites are altered to aluminous chromites. Chromites showing magmatic replacement textures are thought to have formed by reaction with a late, residual melt of anorthositic composition, for their compositions are very similar to those of chromites found in Archaean anorthosites.

The close association between the Fe^{3}+-Cr-chromites of the main trend and Al-rich chromites of the type found in anorthosites strongly supports the view that anorthositic chromites evolve from a basaltic parent magma.

Rosing

Geochemical evidence for the early metabolic activity

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Abstract not submitted
before extended deadline

Strauss

The early Archaean sulfur-cycle - evidence from sulfur isotopes

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Introduction

Unraveling Earth´s earliest evolution encompasses studies of the stable isotopic composition of redox-sensitive elements such as sulfur in sedimentary rocks with the objective to determine the composition of ancient seawater and the activities of microbial life. A prerequisite for such studies are sedimentary successions which have suffered little metamorphic or structural overprint, thus, allowing to assess primary depositional features and reconstruct ancient sedimentary systems. Archaean sedimentary successions in southwest Greenland, southern Africa, western Australia and North America have been studied in that respect and sulfur isotope results were presented in a recent compilation by Strauss (2001).

Conceptual Approach

For sulfur, the traditional approach has been the analysis of calcium sulfate from evaporite deposits and sedimentary pyrite, predominantly from clastic successions. The sulfur isotopic composition of the latter has been utilized as evidence for biogenicity, based on comparison with datasets from geologically younger deposits or modern marine sediments. The difference between both isotopic compositions and an isotope mass balance are interpreted with respect to element cycling between the reservoirs of oxidized and reduced sulfur as a consequence of geological and biological processes.

Available Evidence

Extremely limited information exists in respect to the isotopic composition of Archaean seawater. Data have been measured for early Archaean barites from southern Africa, western Australia and India, and for trace quantities of sulfate in carbonates of late Archaean age from southern Africa and western Australia.

In contrast, a substantial body of sulfur isotope data exists for pyrite from all major sedimentary successions of Archaean age. For most studies, tracing the antiquity of bacterial sulfate reduction, the prime process of biological sulfur cycling in marine sediments, has been the central objective.

Current Controversies

Implications for the biological sulfur cycling resulting from modern marine sediments are not solely based on absolute sulfur isotope values for sedimentary pyrite. Instead, most studies also consider the isotope difference between sulfate and sulfide. This is related to the pertaining environmental conditions.

Two schools of thought exist in respect to interpreting the sulfur isotopic composition of Archaean, more precisely early Archaean, sedimentary pyrite. Respective sulfur isotope

values display a narrow range in 34S centered around 0 ‰, which is close to values for magmatic sulfur. Larger variations in the sulfur isotopic composition of sedimentary pyrite appear to be characteristic only in late Archaean and subsequent times. This is interpreted to reflect the onset of a predominantly biological sulfur cycling, as evident from an enhanced sulfur isotope fractionation between seawater sulfate and reduced sulfide.
Alternatively, the same sulfur isotope record is interpreted to reflect bacterial sulfate reduction under environmental conditions (such as high reduction rate and low sulfate concentration) favoring greatly attenuated sulfur isotope fractionation.
One of the crucial caveats is the extremely limited knowledge of the sulfur isotopic composition of ambient seawater sulfate. Current knowledge is based on sulfur isotope measurements for barites which were thought to represent pseudomorphs after evaporitic calcium sulfates. However, a hydrothermal origin for these barites has been suggested most recently. Moreover, analyses of mass-independent sulfur isotope fractionation are interpreted to reflect a strong influence of atmospheric sulfur chemistry. Additional measurements on early Archaean sedimentary pyrites cast doubt on their proposed biological origin.

Temperley

The tectonic significance of multiphase shearing in the Itsaq gneiss complex, Isua, SW Greenland

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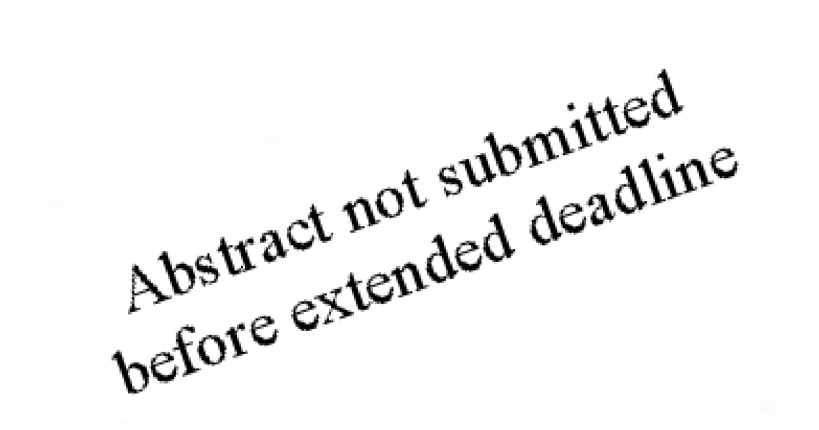

Tolstikhin & Hofmann

Generation of a long-lived primitive mantle reservoir during Earth accretion

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Global geochemistry and seismology have recently produced increasingly conflicting views of the Earth’s deep interior. Several independent lines of geochemical evidence have continued to favor models of a layered mantle, in which primordial noble gases, heat production, and regions relatively rich in highly incompatible trace elements are located in the deep mantle. These models have traditionally assumed that the 660-km seismic discontinuity marks the boundary between the upper-mantle depleted and the lower-mantle “primitive” reservoir. They are to a significant extent based on observations of noble-gas abundances in oceanic basalts, and on mass balance considerations involving essentially three silicate reservoirs, the continental crust, a “depleted” mantle reservoir (which generates MORB) and an undepleted mantle reservoir. Although the debate continues whether the geochemical evidence can be explained by other, usually more complex models, there is little question that the reservoir models provide the simplest and most straightforward explanation of the observed geochemical and heat budgets. Nevertheless, these models are increasingly falling into disfavor because (a) there is also compelling geochemical evidence that no oceanic basalts are produced by direct melting of a primitive mantle reservoir, and (b) the images of the seismic velocities produced by seismic tomography show little evidence for mantle layering, but instead give strong indications of very deep subduction. Thus, the simplest explanation for this evidence is whole-mantle, rather than layered convection. Such whole mantle convection implies that the long-term chemical “identity” of the sub-660 km mantle and of the depleted, upper mantle would be destroyed over time.

Kellogg et al. (1999) finally broke the “rule” which had previously fixed the putative boundary between the reservoirs at 660 km depth und proposed the existence of a much smaller, compositionally dense, primitive reservoir in the deep mantle. They did not, however, explain how such a reservoir might come into existence in the first place. Here we propose such a mechanism. Although our proposition is, by necessity, speculative, we argue that our scenario is a highly likely outcome of current accretion models.
Current accretion histories typically require 5 107 to 108 years and they link the formation of the moon with the impact of a giant planetesimal, the formation of a terrestrial magma ocean and core formation (Weidenschilling 2000; Wetherill and Inaba 2000). This cataclysmic event probably took place about 4.50 Ga ago, and it did not mark the end of accretion. Rather, impacts of smaller bodies continued with decreasing frequency. Evidence for these can be seen on the surface of the moon itself, and some of this activity has been referred to as “late heavy bombardment.” At this time, most of the Earth had been accreted, but core segregation and basaltic crust generation and subduction were continuing

at lower rate. The larger of the late incoming bodies probably triggered additional melting and segregation of liquid iron, but a significant portion of the late-accreting, chondritic material was simply added to an early-formed crust without extensive melting and consequent segregation of metallic iron. Portions of the early crust were therefore significantly enriched in iron. When these portions were subducted and converted to an eclogitic assemblage, the bulk density of the some of subducted lithosphere in the deeper mantle was significantly greater than that of ordinary “primitive “ mantle, which had lost its metallic iron to the core. The density of ordinary chondritic material is about 4.3 g cm-1. Thus, if some portions of the ancient crust contained about 10% chondritic material, its zero-pressure density would be increased by about 4 %, and this increase would be further enhanced by conversion to eclogite during subduction. Consequently, the mechanism of segregation and long-term storage of subducted crust at the base of the mantle, as proposed by Christensen and Hofmann (Christensen and Hofmann 1994), would be significantly enhanced. These authors had assumed that the density difference between eclogite and lherzolite would be preserved even when subjected to further phase transformations (to magnesiowustite and perovskite) in the deep mantle. This assumption has since been shown to be probably invalid by density data of Kesson et al. (Kesson et al. 1998) who showed that, at lower-mantle pressures, the mineral assemblage of basaltic chemical composition is no denser than a pyrolite composition. However, the high iron content of the “chondrite-enhanced” crust will almost certainly overcome this handicap and will preserve a significantly higher density relative to pyrolite.

Segregation at the base of the mantle of this dense material will be facilitated by the high temperatures at the core-mantle boundary, which greatly reduce the viscosity, as was quantitatively modeled by Christensen and Hofmann. This material is likely to have the following additional properties: (1) It will contain on the order of 5 times greater concentrations of U, Th, and other highly incompatible elements, assuming that the early crust was formed by 20% partial melting of the primitive mantle. (2) It will be enriched in primitive rare gases because the small incoming debris will have been subjected to intense solar wind. This material is thus expected to contain about 2.5 .˜ı. g gas-rich material with about 10 –2 cc g-1 He per g of the infalling material, or 10 –5 cc g-1 of the basaltic crust. We emphasize that these are very rough estimates. Moreover, even a low probability for the formation and survival of such material would suffice to form and preserve a primordial rare-gas-rich reservoir (hereafter referred to as PR3), which would satisfy all of the requirements of geochemical mass balances and evolution scenarios. Calculations using the present day fluxes of 3He and 129Xe from the mantle and the 129Xe budget of the atmosphere provide an estimate of the minimum mass of PR3 needed to sustain these fluxes and budgets through Earth history (Tolstikhin and Marty 1998). This minimum initial mass would be merely 15% of the lower-mantle mass, provided the above estimates for the concentrations of U and primordial rare gases are correct.

We conclude that an extended history of Earth accretion provides a plausible scenario for creating a relatively small, density-stabilized PR3 reservoir, which is rich in primordial noble gases and in heat-producing elements. Initially, about 2/3 of the total inventory of the heat producing elements may have been concentrated in this reservoir, and this would have important consequences for the evolution of the Earth’s core, mantle, and continental crust. Mantle plumes are likely to be generated in the boundary layer between this deep reservoir and the overlying ordinary mantle. Noble gases may migrate into this boundary layer and thus into the plume sources, and small amounts of PR3 material may be entrained by the plumes without otherwise dominating their compositions.

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Touret et al.

Fluid inclusions in Isua supracrustals: what they can tell about Earth's surface conditions at about 3.7-3.8 Ga

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Isotope systematics (ion microprobe U-Pb zircon ages, Nutman et al., 1997, Whitehouse, 2000, Sm-Nd regression line, Moorbath & Whitehouse, 1996, Rosing, 1999) bracket the depositional age of Isua supracrustals, West Greenland, to a ca. 3.7-3.8 Ga interval, at the end or shortly after the intense early metorite bombardment which hit the Moon (and most probably the Earth) in Hadean times. Despite a complicated metamorphic history, with presumably two major metamorphic episodes, one early Archean, the second late Archean at ca. 2.87 Ga (Rosing & Frei, in press), a number of supracrustal occurrences, volcanic, volcanoclastic or sedimentary, show well-preserved syndepositional structures, such as pillow-lavas, pillow breccias, sedimentary layering, which leave little doubt about the pre-metamorphic nature of the protoliths (Appel et al., 1998, Solvang, 1999). They correspond to a typical Greenstone Belt type association, with a majority of intensely altered basic effusives, metacherts, banded iron formation (BIF) and relatively minor metasediments (pelites, possibly conglomerates). All rocks show now a typical metamorphic mineral assemblage (biotite, garnet), equilibrated at a temperature of about 500°C and a pressure of few kbars (Appel et al., in press). Despite a relatively high grade, this metamorphism is truly remarkable by a locally weak pervasive schistosity, which in few « low-strain » areas is unable to obliterate pre-metamorphic features (Appel et al., 1998, Solvang, 1999). Metamorphic textures are characterized by an intense static recrystallization (annealling) of many rock-forming minerals, notably quartz, occurring as unstrained crystals limited by straight or gently curved boundaries and equlibrated (120°) triple junctions. This annealling probably occurred during the second (late Archean) metamorphic episode. Post-metamorphic uplift took place along prominent, subvertical shear-zones, as the one containing the famous « greenlandite » (fuchsite-bearing quartzite) occurrence.

The peculiar metamorphic history has a drastic influence on fluid inclusions, much smaller (typically few microns in size) and less abundant than in most metamorphic complexes of comparable grade. Enough workable inclusions however document two major types of fluids, found repeatedly (but in very different relative amounts) in all types of supracrustals studied so far: high-salinity (up to about 50 wt % NaCl equivalent) aqueous fluids (brines) and pure gazeous inclusions, always containing methane (CH4). In many protoliths, notably BIF, the gaseous inclusions appear to be empty, but their walls are coated with very small graphite particles. We believe that these may correspond to the « microscopic graphite globules » described by Rosing (1999) or Mojzsis et al., 1999). These show a light carbon isotope signature, interpreted by these authors as an indication of possible biogenic activity. All inclusions show considerable evidence of in situ decrepitation, caused by internal fluid overpressure during postmetamorphic uplift. This « transposition » did not exceed however the size of the host crystal, and it indicates that post-metamorphic uplift occurred by isothermal decompression (Touret, 2001), in line with the vertical orientation of the late shear zones. These, notably at the greenlandite occurrence, have drained a considerable amount of brines, able to transport a number of metallic components, e.g. chromium.

In most cases, the fluid origin is not easy to demonstrate. An exception is for inclusions found in undeformed, subcircular vesicles occurring in few fragments from pillow-breccias (Appel et al., in press). These vesicles are thought to represent former gas bubbles in the ascending magma, filled with silica-rich material (opal, calcedony, eventually quartz) and later recrystallized during metamorphism. The rock itself is entirely made of quartz, feldspar, biotite, muscovite, accessory opaques and tourmaline, indicating that the basalt had been completely altered in a mixture of silica-rich clay minerals immediately after eruption. The extent of alteration is further indicated by the rare occurrence of polygonal quartz aggregates, mantled by a dark (Fe-rich) boundary, which could correspond to the pseudomorphose of former mafic magmatic minerals, notably olivine.

Several lines of evidence indicate the primary character of the few inclusions found in some of these vesicles, which are believed to contain remnants of pre-metamorphic, hydrothermal fluids: isolated or clustered inclusions, associated to minute carbonate crystals which belong to the former alteration mineral assemblage, primary inclusions found in remnants of geodic lining, etc. Arguments are strong for the brines, less obvious for the gaseous inclusions (methane) which might also have been partly formed or re-equilibrated at a later stage (metamorphic). Estimated fluid composition, not easy to establish because of late inclusion transposition, fall within the range of present-day hydrothermal sea-floor alteration fluids. The possible occurrence of methane, as well as the type of alteration (abundance of silica-rich material, clay minerals of illite-type), are also in line with present-day findings at mid-oceanic ridges. A direct consequence is that the Earth's surface at Isua was indeed covered by sea, but also that the sea salinity and, in a more general way, the characteristics of sea-floor hydrothermal alteration were not drastically different of what they are today. This environment provides evidently optimal conditions for the life to develop, but we must say a word of caution about a too fast interpretation of the stable isotope (carbon) signature. The low δ 13 C values, both in carbonate (Schidlowski et al., 1979) and graphite (Rosing, 1999, Mojzsis et al., 1999), suggest indeed a possible biogenic activity (Mojzsis et al., 1996). However, what we presently see in the rocks suggest mainly pure chemical interaction, at P-T conditions which as a whole were largely outside any reasonable conditions for the apparition of life. As long as we will not have found remnants of micro-organisms, which if once existing should have left some traces in so well preserved protoliths, it is not easy to say unambiguously if the rock-fluid system at Isua was purely chemical, or if it did involve some kind of biological activity.

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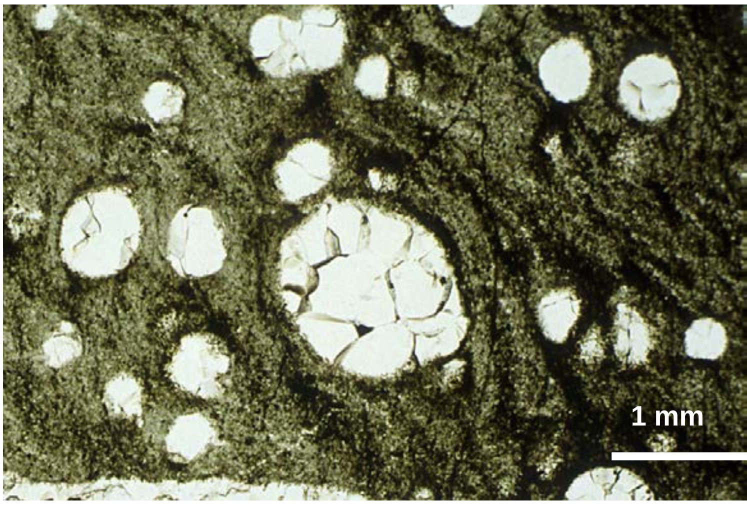
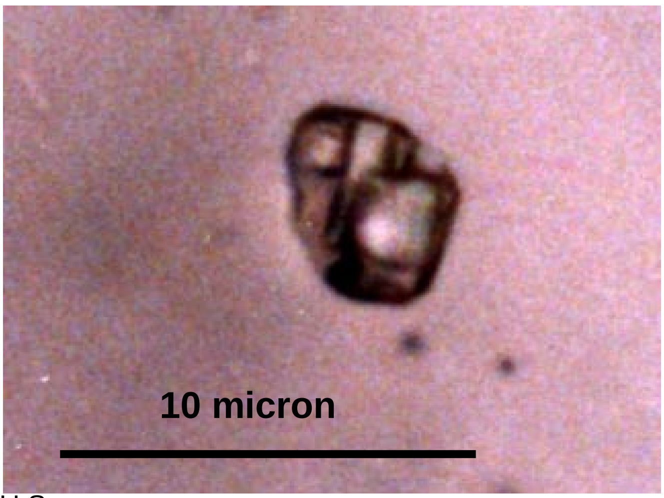
Pillow breccia

Thin section of pillow fragment





Inclusion in quartz with gas, solid and fluid

Westall

No Early Archaean fossil bacteria in cherts from Isua

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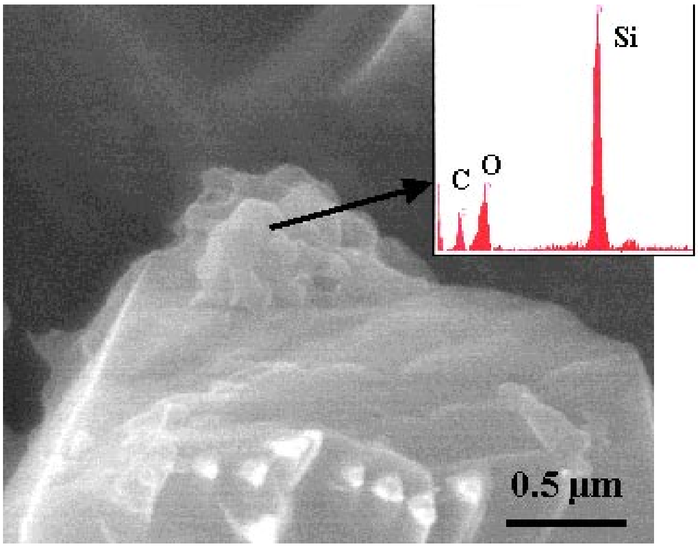
Cherts and BIFs from the low strain zone of the Isua greenstone belt were extensively inspected for their potential microfossil content using a high resolution FEG-SEM with attached light element EDX capability. No indigenous fossil bacteria were observed, although graphite crystals and silicified amorphous kerogen were present. On the other hand, the BIFs were heavily infested with younger (<2000 y. old), fossilised endolithic cyanobacteria and fungal hyphae.

Over the last 6 years I have developed reliable criteria for the identification of fossil bacteria and the extracellular polymeric substances (EPS) in Early Archaean (>3.4 b.y. old) cherts from Barberton and the Pilbara, based on macroscopic to microscopic study (thin sections and high resolution FEG-SEM plus light element EDX capability) (Westall, 1999; Westall et al., 2000; Westall et al., 2001; Westall, in prep.). These methods have revealed the extensive development of microbial mats on the surfaces of volcaniclastic sediments deposited in shallow water, intertidal and perhaps subaerial environments (Westall et al., 2001; Westall in prep.). The microorganisms in the mats from Barberton and Pilbara include (i) fine filaments, 0.1-0.5 µm in diameter and up to 10 µm or more in length, (ii) rod-shaped bacteria, 1 µm in diameter and 2-3.8 µm in length, and (iii) coccoidal or oval bacteria, 0.5-1 µm in diameter. They are all associated with copious quantities of EPS. The mats form macroscopic to microscopic tabular or domal stromatolites. They were preserved by precocious hydrothermal silica impregnation, although not before most of the organisms had been partially degraded. The geological settings of the coeval Barberton and Pilbara greenstone belts are identical: mainly shallow water volcaniclastics (and some rare, intertidal to subaerial deposits) intercolated with basaltic-felsic lavas, all strongly influenced by hydrothermal activity. There are no deep-water sequences preserved in these > 3.4 b.y. horizons.

The rocks at Isua have been so strongly metamorphosed and strained that, in most cases, their protolithic nature has been more or less obliterated. There is much discussion as to whether the remaining protoliths indicate a quiet, deep-water regime (Cas et al., 2001) and/or shallow water to subaerial regimes (Fedo, 2000). In the latter case, they would represent a similar suite of lithologies to those represented in Barberton and the Pilbara greenstone belts, which are not much more than 200-300 m.y younger. Taking this latter analogy further, given the well-developed diversity of the bacteria in the Barberton and Pilbara cherts, and their apparent widespread distribution, life could have been present in appropriate habitats in Isua times (including deep water environments).

A number of cherts and banded iron formations samples from a low strain area, as well as a chert sample from a fold hinge in a BIF from Iron Mountain, were investigated using a high resolution FEG-SEM with light element EDX for evidence of microfossils. Numerous preparations of the same sample (delicately HF-fume etched thin section, unetched and etched rock chips and cut rock surfaces) were prepared in such a way as to exclude the introduction of artifacts or the importation of extraneous "dirt". However, none of the samples contain morphological evidence for indigenous fossil bacteria. Small, silicified, amorphous to stringy structures, 1-10 µm in size were observed, sometimes occurring together with euhedral micrometer-sized graphite crystals. They contain a (qualitatively) small amount of C. The occurrence of these structures in multiple types of preparations demonstrates that the graphitic and silicified kerogenous structures are indigenous. Graphite of metamorphic origin has previously been described from these cherts (van Zuilen et al., 2000), but this is the first description of indigenous, silicified amorphous kerogenous structures.
The amorphous nature of the silicified kerogen precludes any direct interpretation of their origin. The kerogen may have originated either from abiotic carbon or from biogenic carbonaceous matter. C-isotope ratios from the Isua/Akilia cherts have been used to demonstrate a diverse microbial presence in this area between 3.7-3.85 b.y. ago (Schidlowski, 1988; Mojzsis et al., 1996; Rosing, 1999). However, the possibility of the production of graphite having a "biogenic signature" by metamorphic processes has been raised (van Zuilen et al., 2000). Moreover, my own FEG-SEM investigations of the cherts have brought to light massive infiltration by endolithic microbes of cherts in a number of BIF formations. The infiltrating microorganisms consist of (i) chains of ~ 3-5 µm diameter spheres coated with a thick outer layer of EPS, (ii) more irregular accumulations of similarly-sized spheres embedded in EPS, (iii) 1 µm sized collapsed oval structures, and (iv) branching filaments, 10s µm long and a few micrometers wide, also associated with EPS. All four types of structures occur on fracture planes and along the boundaries of grains. The morphology of these structures strongly resembles that of bacteria (smaller ovals) and cyanobacteria in the case of the (larger) spheres, and offilamentous bacteria or fungal hyphae in the case of the filaments (N.B. lichens were observed on the surfaces of the rocks). Cracks in the structure of the organisms and in their associated EPS, as well as a strong Si peak in the EDX spectrum, demonstrate that the microbes have been silicified, although strong C peaks in the EDX spectra show that there is still much carbonaceous matter trapped within the silicified biogenic structures (compared to the indigenous amorphous kerogen). Their distribution along intergrain cracks and fracture planes suggests that the microorganisms represent endolithic intrusions. Endolithic behaviour in bacteria and fungi is typical in extreme environments such as hot or cold deserts (Wynn-Williams and Howell, 2000). The rocks at Isua are exposed in just such a cold, dry environment.
When could the infiltration of these microorganisms have taken place? The Isua area remained covered by the Greenland Ice Sheet until about 2000 y ago. The surface exposed today would have been ground down by the base of the ice sheet. As the ice sheet retreated, the "freshly ground" surface would have been exposed. Thus, it may be concluded that the endoliths penetrated the cherts and become silicified within the last 2000 y. (N.B. the silicification of microbes can take place within one day).
The presence of these endoliths needs to be taken into account in any search for evidence for life in these rocks. Isotopic measurements of bulk samples may produce a false posi-

tive signal. Moreover, acid-digestion of the cherts will liberate any endolithic microorganism, thus producing another false positive signal.



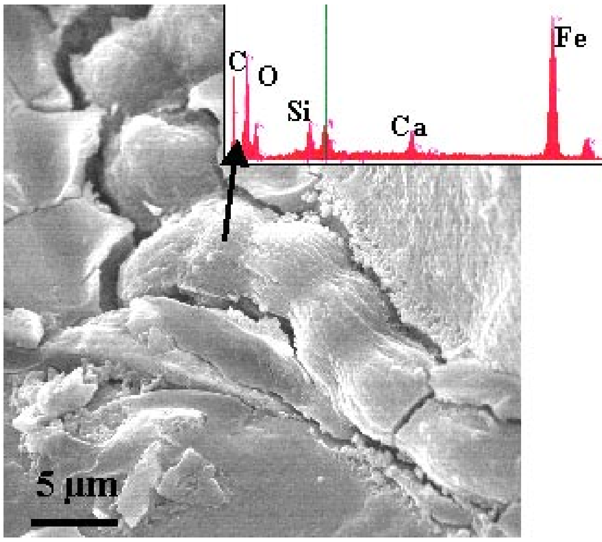


Fig. 1. Silicified, amorphous clump of kerogen in metachert.

Note small C peak.

Fig.2. Silicified, endolithic cyanobacteria in crack between magnetite grains. Note larger C peak and cracks in organism and surrounding EPS indicating mineralisation.

In conclusion, a priori it is probable that the ancient Isua/Akilia greenstone terranes could have hosted microbial mats, but the identification of an original biogenic signal is fraught with pitfalls such as metamorphic overprint and endolithic contamination. The challenge is how to distinguish the original signal. Perhaps the stepped combustion method used for identifying indigenous carbon in martian meteorite ALH84001 (Grady et al., 1994), together with careful in situ studies of the apparently remnant structures (e.g. the amorphous kerogen) would be suitable.

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White

Geochemistry, age and implications of dyke swarms in the Isua region

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Introduction

Mafic dyke swarms constitute a conspicuous part of the outcrop in the Isua area, located approximately 150 km to the north-east of Nuuk. This area, part of the Archaean craton of southern West Greenland, contains the Earth's oldest supracrustal rocks: the ~ 3.8–3.7 Ga Isua greenstone belt (also known as the Isua supracrustal belt, and hereafter referred to as the Isua belt). The Isua belt has an intensely deformed contact with 3.8–3.65 Ga tonalitic gneisses that are broadly contemporaneous with the tonalitic Amîtsoq gneisses elsewhere in the craton. This contribution describes field investigations of the dykes carried out in 1999 as part of the Isua Multidisciplinary Research Project, and summarises results from geochemical and geochronological studies.

Summary of field observations

Three major episodes of dyke intrusion have occurred in the region. At least two of these post-date the juxtaposition of the Isua belt with the adjacent tonalitic gneisses.

Episode 1: Inaluk dykes

The oldest (early Archaean) dykes were observed in the northern gneisses (Fig. 1). These sparse dykes, termed the Inaluk dykes by Nutman et al. (1983) cut previously deformed tonalitic gneiss and were themselves intruded by sheets of pegmatite and granite during the deformation that formed the regional gneissosity. These dykes are generally 20 cm to 4 m wide and range from mela-dioritic to tonalitic. Most are melanocratic, containing hornblende and biotite with plagioclase feldspar and some quartz.

Episode 2: Tarssartôq dykes

The second episode of dyke intrusion (Table 1) forms the focus of this study. These dykes have been correlated with the Ameralik dykes of the Nuuk region (Bridgwater & McGregor, 1974), but the correlation is not proven, and I follow the recommendation of Nutman et al. (1983) and refer to the dykes in the vicinity of the Isua belt as Tarssartôq dykes. The volumetrically important, predominantly basaltic, dykes are a few cm to about 100 m thick, and post-date the cessation of early Archaean plutonism, metamorphism and deformation. In some locations, particularly within and to the south of the Isua belt, they are affected by late Archaean metamorphic events. Within the gneisses encircled by the Isua belt, the Tarssartôq dykes are undeformed and largely preserve their original igneous mineralogy.

The Tarssartôq dykes are subdivided into distinct swarms. Cross-cutting relationships between dykes were used to reconstruct the order of intrusion of the different swarms. Swarms have the prefix 'T' (Tarssartôq) and are numbered, with T1 being the oldest swarm. With the exception of the N–S-trending T3 swarm, all swarms have approximately E–W orientations in the area of gneisses bounded by the Isua belt. No cross-cutting relationships were observed between the T1 and T2a dykes, and their relative positions in the sequence are based on geochronological data (see later). The T1 dykes are noritic in composition; T2a, T2b and T3 dykes are doleritic. T2b and T3 dykes may contain relict plagioclase megacrysts. A pre-T1 phase of NNE–SSW-trending ultramafic dykes reported by Nutman (1986) was not observed during this study. At Isukasia (sensu stricto), the folding of the dykes makes it difficult to assign them to one of the above swarms based on field relations alone. However, the geochemical composition (see later), presence of occasional megacrysts, and occasional cross-cutting relationships indicate that the majority belong to swarms T2b and T3.

Episode 3: Proterozoic dykes

The youngest episode of dyke intrusion post-dates the late Archaean metamorphism, and resulted in the emplacement of volumetrically minor, mainly N–S-trending norite dykes, in which igneous mineralogy is widely preserved. One of these dykes has yielded a SHRIMP U–Pb zircon age of ~ 2.2 Ga (Nutman et al., 1995).

U–Pb zircon and baddeleyite geochronology

U-Pb analyses have been obtained on zircon and baddeleyite separates (single grains or multi-grain fractions) from six dykes. A summary of the data is shown in Table 2. All analysed minerals had high original U contents and yielded discordant results, in spite of being abraded. For four dykes, the data yield discordia lines, with the upper intercept interpreted as the crystallisation age. In two cases there were insufficient good analyses to give discordia lines, and the values given are 207Pb/206Pb ages, equivalent to minimum age estimates. The T2b and T3 dykes are low in incompatible elements and do not readily yield dateable minerals. The limited data obtained during this study place only very poor constraints on the ages of these dykes, for example, the T3 dykes could have been emplaced at any time between ~3470 and ~2800 Ma.

Table 1. Results of U-Pb zircon and baddeleyite geochronology of Isua dykes

Sample	Swarma	Nr. of analysesb	Age (Ma)c	Discordance (%)
466777	Pre-T1	3Z	3634 ± 8	8.4 –14.7
464137	T1	4 B	3482 ± 10	3.8 – 7.9
464138	T2a	6 Bc, 2 Zc, 5 Z, 5 ZBc	3472 ± 16	3.0 – 25
464140	T2a	4 Bc, 3 Zc, 2 Z	3469 ± 14	0.9 – 8.3
466776	T2b or T3	2Z	3396*, 3321*	7.5, 6.1
466728	T3	2B	2803*, 2697*	6.3, 6.4

a See text and Table 2 for more information about different swarms. Samples 466776 and 466777 are deformed dykes from Isukasia; they are assigned to numbered swarms based on geochemical

b Indicates number and type of fraction analysed: baddeleyite (B); zircon (Z); zircon+baddeleyite composite grains (ZBc); baddeleyite from composite grains (Bc); zircon from composite grains (Zc).

c Dates quoted with errors are upper intercept discordia ages; dates with * are 207Pb/206Pb ages and should not be read as meaningful indicators of crystallisation age.

Petrological and geochemical characteristics of Isua dykes

Petrological and geochemical characteristics of the dykes in the Isua area are given in Table 2. Each group of dykes has a distinct chemical signature, with the exception of the chemically indistinguishable T2b and T3 (low-Mg subset) dykes. The folded dykes at Isukasia (sensu stricto) are too altered for major elements such as MgO and SiO2 to be useful in their classification. However, for most of these dykes, contents of the relatively immobile elements are identical to those in the T2b and T3 swarms. Dykes at amphibolite facies in the southernmost part of the Isua belt also preserve immobile element signatures that are consistent with the field assignation of their swarm. Hence it is concluded that careful geochemical analysis of immobile elements in mafic dykes (up to amphibolite facies) from elsewhere in the region can be used as a tool to assign the dyke to one of the swarms described herein, and hence to place some constraints on its age.

Table 2. Occurrence and general petrological and geochemical characteristics of dykes in the Isua area

Swarm[a]	Trend[b]	Mineralogy[c]	MgO wt.%	SiO2 wt.%	(La/Sm)N[d]	(Sm/Lu)N[d]	ΔNb[e]	Contamination?
Inaluk	folded	hbl + bi + plag ± qtz	13.3–1.3	45.0–65.0	~ 2.3	~ 7.9	-0.24	significant
T1	E–W	opx + plag ± cpx ± ol ± cr ± il ± mag	20.7–18.5	~ 52.5	2.9–3.3	1.5–1.8	-0.26	significant
T2a	E–W	cpx + plag + mag + il (+ amph)	8.7–5.6	47.9–50.6	1.5–2.1	~ 1.5	+0.02	possible
T2b	E–W	cpx + plag + mag + il ± ol (+ amph)	8.0–6.7	48.3–49.7	0.8–1.0	1.1–1.3	+0.07	insignificant
T3	N–S	cpx + plag + mag + il ± ol (+ amph)	13.4–11.3	47.7–48.5	~ 1.0	~ 1.6	+0.08	insignificant
			9.3–5.8	47.5–49.8	0.8–1.0	1.1–1.3	+0.07	insignificant
Prot.	Mainly N–S	cpx + opx + plag (+ amph + bi)	11.2–3.9	48.4–54.8	2.4–3.2	2.3–3.3	-0.18	significant

a Prot. – Proterozoic; T – Tarssartôq.
b Approximate trend given for dykes that are not folded.
c Minerals that are clearly secondary are given in parentheses.
d Chondrite-normalised values given
e ΔNb (Fitton et al. 1997) gives indication of source depletion for uncontaminated samples; primitive mantle has ΔNb ≈ +0.18 and depleted mantle has ΔNb < 0; crustal rocks generally have negative ΔNb.

Conclusions

- All information yielded by this study is consistent with the proposed correlation between the Tarssartôq and Ameralik dykes.
- None of the dykes, with the possible exception of high-Mg group of T3 dykes, represent primary, unmodified, mantle-derived magmas. The presence of plagioclase megacrysts

also suggests that the parental dyke magmas have undergone fractionation in long-lived magma chambers.

- The Inaluk, T1 and Proterozoic dykes all have geochemical features consistent with significant contamination by tonalitic gneiss. In some cases, the enrichment in incompatible elements is too high to have been generated by contamination alone, and a trace element-enriched mantle source must be invoked.
- There is a general trend with time in the Tarssartôq dykes from more to less contaminated, with melting also occurring at progressively shallower depths. Remarkable geochemical similarities between the T2b and T3 dykes and Phanerozoic oceanic large igneous provinces suggest that the dyke source had a potential temperature close to that of a Phanerozoic mantle plume.
- There is no evidence for derivation of any Isua dykes from strongly depleted mantle. These data can only be reconciled with the assertion that "extremely" or "moderately" depleted mantle contributed to the Isua supracrustal rocks at 3.8 to 3.7 Ga (Bennett et al., 1993; Blichert-Toft et al., 1999) if the mantle source material for the Isua volcanic rocks was removed by vigorous mantle convection and replaced with less depleted mantle prior to dyke magmatism.

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Whitehouse & Fedo

No BIF means no life! New geological and geochemical observations from Akilia

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Is the Earth's earliest life preserved on Akilia? The spectacular claim that low ^{13}C values of graphite inclusions in apatites from an amphibolite-hosted quartz-pyroxene layer (so-called banded iron formation of “BIF”) on Akilia (Mojzsis et al., 1996) has sparked impassioned debate, particularly because these rocks have further been claimed to exceed 3.87 Ga (Nutman et al., 1997), ca. 100 Ma older than other proposed early life bearing rocks at Isua. Given the significance of this age in terms of its likely overlap with the late heavy meteorite bombardment of the Earth and consequent life-frustrating environment, much of the debate to date has focused upon the interpretation of geochronology and isotope geochemistry from claimed cross-cutting tonalitic gneisses and, to a lesser extent, the host amphibolites (Kamber & Moorbath, 1998, 2000; McGregor, 2000; Whitehouse et al., 1999, 2001; Nutman et al., 2001; Myers and Crowley, 2000). In this geochronological debate, most authors have generally accepted that the low ^{13}C values are indeed evidence for life, with the notable exception of Myers and Crowley (2000) whose detailed study of intense deformation and metamorphism on Akilia moved them to use the term “miraculous” in describing this evidence. Regrettably, detailed descriptions of the “ BIF” on Akilia are conspicuously absent in the literature. Indeed, the only “evidence” so far proposed for a sedimentary origin of the quartz-pyroxene layer, an obvious pre-requisite for its hosting life, comes from an interpretation based on its “...magnetite layering and by comparison with other units such as in the Isua supracrustal; belt...” (Nutman et al., 1997) . The study we report here concentrates on field and geochemical characteristics of the quartz-pyroxene layer, itself, as well as the adjacent amphibolites and pyroxenites. We make no further comment on the geochronological debate beyond pointing out that our own observations of deformation on Akilia, including unambiguous structural discordances in the tonalitic gneisses, lead us recommend extreme caution in any interpretation for the age of the amphibolites that is based on geochronology of these gneisses.

Our observations of the Akilia quartz-pyroxene layer and its surrounding rocks are based upon new fieldwork and sampling undertaken during 2001. A simple, first-order observation is that claimed similarity with unequivocal BIF in the Isua greenstone belt is, at best, misleading. A detailed, measured (cm-scale) “stratigraphic” section across the ca. 5m wide “BIF” from its eastern boundary with ultramafic lithologies to its western boundary with amphibolites, reveals that only two sub-layers, constituting about 15% of the entire quartz-pyroxene layer, contain modal magnetite. Throughout the unit “banding” is formed primarily by quartz and pyroxene alternations, not quartz and magnetite, or amphibole and magnetite, as at Isua. Boudinaged layers of pyroxenite typify the unit, and occurs at various scales; indeed the entire 5m-wide layer is itself part of a larger scale boudin. On the smallest scale, many thin mafic bands (pyroxenes) represent tails of highly stretched boudins. We suggest that heterogeneous strain during deformation might itself be responsible for the generation of fine laminations, rather than their being primary sedimentary structures that have escaped “perturbation” by meteorite bombardment (Mojzsis et al., 1996). A very coarse, post-tectonic, granoblastic texture obscures much of the rock’s high-strain history.

Interpretation of major and trace element geochemistry of representative samples across the quartz-pyroxene unit as well as adjacent lithologies is presently at an early stage. Initial impressions, however, are of extreme trace-element heterogeneity that points away from a simple sedimentary origin for the unit. However, the polyphase nature of the unit, and likely substantial post-formation geochemical modification, merits considerable caution in any interpretation of geochemical data.

The very presence of low ^{13}C graphite and its association with apatite is commonly postulated as unambiguous support for the sedimentary origin of the unit and its hosting of early life. Any suggestion of a non-sedimentary origin for the quartz-pyroxene rock must address this issue and, in particular, suggest a mechanism for abiotic C-isotope fractionation. We note that at Isua, Lepland et al. (2001) have described graphite inclusions in apatite from non-sedimentary rocks, suggesting that the association itself is not as unambiguous an indicator of life as previously claimed. Further investigation of the Akilia rocks is under way to assess whether similar abiotic origins may be supported there. Our new modeling calculations for a Rayleigh distillation process to derive isotopically light carbon, while not conclusive, are compatible with known regional geologic conditions.

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A survey of boron isotopes in tourmalines from the northeastern segment of the Isua Greenstone Belt

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Abiogenic and Biogenic Graphite in the Isua Supracrustal Belt

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The principal method for studying the earliest traces of life in the metamorphosed, oldest (> 3.5 Ga) terrestrial rocks involves determination of isotopic composition of carbon, mainly prevailing as graphite. It is generally believed that this measure can distinguish biogenic graphite from abiogenic varieties. However, the interpretation of life from carbon isotope ratios has to be assessed within the context of specific geologic circumstances requiring (i) reliable protolith interpretation (ii) control of secondary, metasomatic processes, and (iii) understanding of different graphite producing mechanisms and related carbon isotopic systematics.

We have carried out a systematic study of abundance, isotopic composition and petrographic associations of graphite in rocks from the ca. 3.8 Ga Isua Supracrustal Belt (ISB) in southern West Greenland. Our study indicates that most of the graphite in ISB occurs in carbonate-rich metasomatic rocks (metacarbonates) while sedimentary units, including banded iron formations (BIFs) and metacherts, have exceedingly low graphite concentrations. Regardless of isotopic composition of graphite in metacarbonate rocks, their secondary origin disqualifies them from providing evidence for traces of life stemming from 3.8 Ga. Recognition of the secondary origin (1,2) of Isua metacarbonates thus calls for re-evaluation of earlier biologic interpretations (3,4) that suggested the occurrence of 3.8 Ga biogenic graphite in these rocks.

Thermal decomposition of siderite; $6FeCO_3 \rightarrow 2Fe_3O_4 + 5CO_2 + C$, is the process seemingly responsible for the graphite formation (5,6). The cation composition (Fe, Mg, Mn, and Ca) of the carbonate minerals, carbon isotope analysis of carbonates and associated graphite and petrographic analysis of a suite of metacarbonates support the conclusion that multiple pulses of metasomatism affected the ISB, causing the deposition of siderite and subsequent partial degradation to graphite and magnetite. Equilibrium isotope fractionation between siderite and graphite in these rocks indicates a temperature of metasomatism between 500 and 600C, which coincides with other estimates of metamorphic temperature for the ISB. The siderite-graphite-apatite association in the ISB consequently appears to be an entirely abiogenic metasomatic feature, which does not point to traces of an ancient Early Archaean ecosystem.

The possibility of recent organic contamination, particularly important in low graphite samples, needs also to be considered. Combustion experiments at different temperature steps

(450, 550, 650, 800, 900 and 1000C) revealed that virtually all reduced carbon present in the BIFs (typically between 40 and 100 ppm), is released below 450C. The $\delta^{13}C$ of this component (approximately –27 per mil) is typical for biologic material, and clearly shows that this is recent contamination. From these results it is suggested that previous observations of low $\delta^{13}C$ values in Isua BIFs (3,8) are not representative of ancient remnants of life. An exception to our observations is a locality in the western part of the ISB, where isotopically light graphite occurs in sequences of graded beds, seemingly representing cyclic turbidites (7). The absence of siderite and/or magnetite makes it clear that inorganic formation of graphite by siderite dissociation can not be the source of carbon in these metasediments. This particular formation in the ISB thus contains the only currently known remnant of Archaean life with a verified age of 3.8 Ga.

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