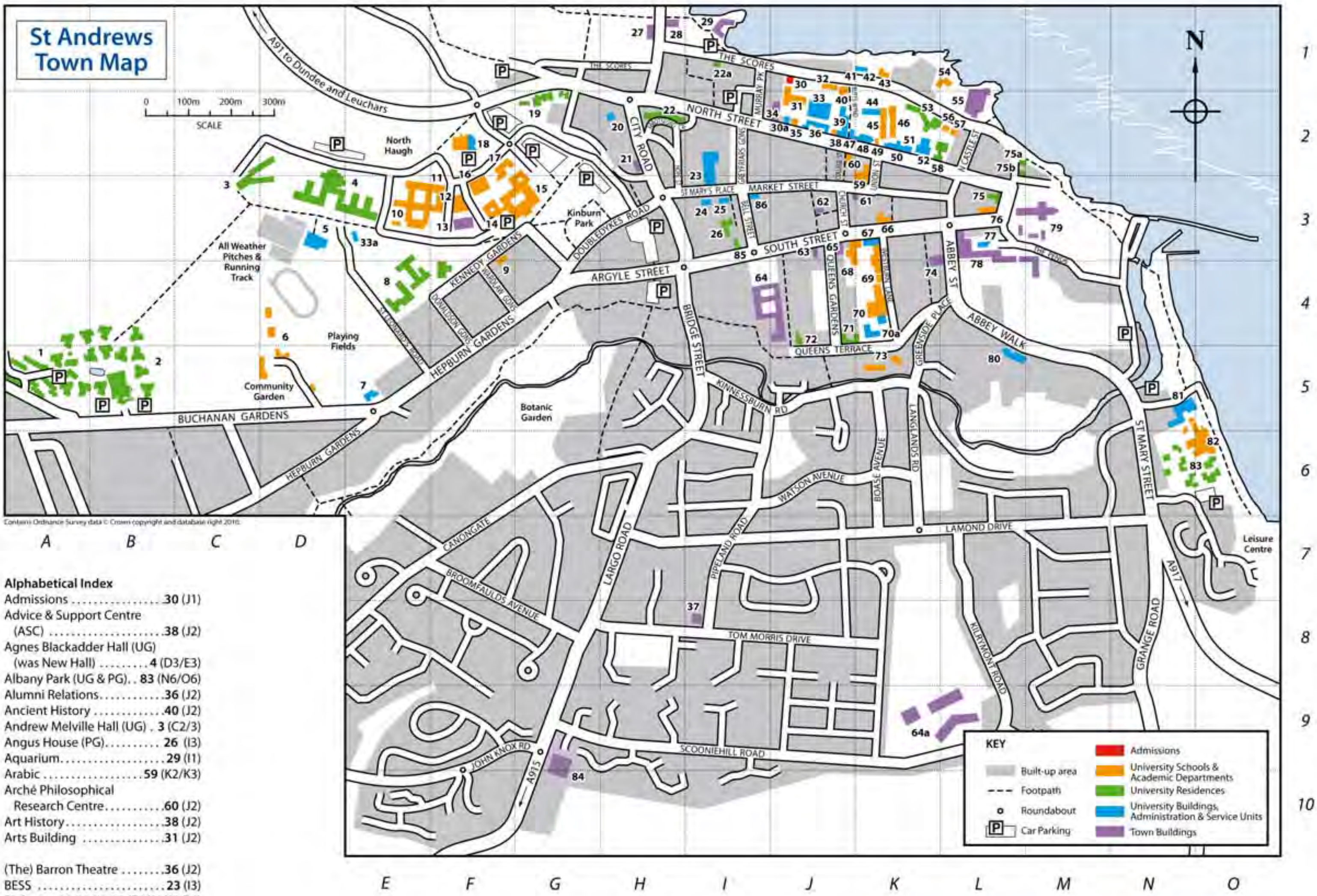
University of St Andrews | 20-21March 2014

North Atlantic Craton Conference 2014

A craton-specific approach to exploration targeting

Programme & Abstracts

www.nac-conference2014.org.uk



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Welcome to

'The North Atlantic Craton Conference:
A craton-specific approach to exploration targeting'

St Andrews 19–21 March 2014

Mineral exploration is becoming more challenging, with most of the visible surface deposits largely already discovered. With our increasingly metal and resource-dependent global society, the demand for all mineral resources is escalating, especially for the 'critical metals' such as the platinum group elements, the rare earth elements, lithium, indium, tellurium, chromium, to name but a few. In addition, the expanding populations of 'BRIC' countries sees greater urban and infrastructure development, requiring more base metals, iron ores, aluminium, and bulk commodities. And as ever, the investment sector sees continued demand for gold production.

Advances in mineral exploration, mining and mineral processing are more important than ever, and have progressed so far that they are becoming unrecognisable to methods practiced during the last century. With increasing environmental awareness, our subject remains at the core of environmental remediation and has facilitated the cultivation of environmental responsibility as operational practice.

More recently, the importance of a craton-specific approach to mineral exploration has been realised. This conference, on the mineral potential of the North Atlantic Craton (NAC) as a whole, is aimed at initiating and furthering trans-Atlantic collaboration in understanding the Archaean cratonic controls on ore deposit formation through time. The Archaean high-grade gneiss terrain of the NAC stretches from Labrador, Canada, through Greenland and into Scotland and many aspects of its geology are common across geographical and political boundaries. Acceleration in exploration efforts for various commodities across this region, particularly in Greenland, has highlighted the potential for its mineral resources. With these opportunities come unique challenges, not least in 'unpicking' the prolonged and complicated history of such ancient lithosphere. Successful exploration is increasingly reliant on 'geology' and 'geological interpretation' and less on straightforward and traditional prospecting techniques. In addition, the retreating ice sheet in Greenland and arctic regions means that many locations, thus far unexplored, are opening up for investigation. With the eyes of the world on these areas of astounding natural beauty, it is essential that mineral exploration and extraction be well designed and impact as minimally as possible on its surroundings ensuring its future legacy.

This conference follows from a collaboration by a group of geologists working on the NAC. Co-ordinated by the NAC Organising Committee in collaboration The Mineralogical Society of Great Britain and Ireland, this is very much a joint effort between numerous academic, government and industry bodies. The event is held under the banner of Cardiff Chapter of The Society of Economic Geologists and the Students and Staff of the Department of Earth & Environmental Sciences of the University of St Andrews, in conjunction with The British Geological Survey (BGS) and The Geological Survey of Denmark and Greenland (GEUS).

This meeting has been arranged around five central themes which we hope will be of interest to all our delegates. There is a poster session and networking opportunities and it is hoped that delegates will make many new contacts, throughout industry and academia, in addition to renewing old friendships.

The organisers take this opportunity to formally thank the Department of Earth & Environmental Sciences at the University of St Andrews for hosting this event. The also the generous sponsors, both in industry and academia, for helping to make the NAC Conference such as success.

CONFERENCE SPONSORS

The North Atlantic Craton Conference Organising Committee would like to thank the generous sponsors of NAC Conference 2014 for their financial support. These include:

- **Northern Shield Resources** *(headline industry sponsors)* for sponsoring the Ni-Cu-PGE session and its refreshment breaks, the drinks and refreshments at the poster session, the conference dinner and ceilidh.
- **The Mineralogical Society of Great Britain and Ireland** for sponsoring keynote speakers. *A Mineralogical Society Hallimond Lecturer for 2014 is Dr Graham Begg*.
- **The Applied Mineralogy Group** for sponsoring the keynote speaker of the Ni-Cu-PGE session, Prof Sarah-Jane Barnes.
- **The Society of Economic Geologists** for sponsoring the keynote speaker of the Au session, Prof Richard Goldfarb.
- **Avannaa Resources** for sponsoring the icebreaker reception.
- **Midland Valley Exploration** for sponsoring the poster board hire for the poster session.
- **Aurum Global Exploration** and **Glasmin Resources** for sponsoring the production of delegate packs and abstract volumes.
- **The Mineral Deposits Studies Group** for providing student bursaries.

ADMINISTRATIVE

CONFERENCE OFFICE

Registration is being handled by Russell Rajendra and Martin Hughes at the Mineralogical Society office. Up to and including Wednesday 12th March, contact details are: Mineralogical Society, 12 Baylis Mews, Amyand Park Road, Twickenham TW1 3HQ; e-mail russell@minersoc.org/ admin@minersoc.org; tel. +44 (0)208 891 6600.

On Wednesday 19th March (7 pm) registration will be open in Parliament Hall during the icebreaker receptoin (see map, no. 67).

From Thursday 20th March (8.30 am), the organisation centre will become the registration/help desk located in the Forbes Room of the Irvine Building, Department of Earth & Environmental Sciences, University of St Andrews (see map, no. 46).

REGISTRATION / HELP-DESK / WELCOMING RECEPTION

All participants should register at the Registration/help desk on Wednesday (19th March) from 7.00 pm (during the icebreaker reception). On Thursday (20th March) from 8.30 am, and onwards, registration will take place in the Forbes Room of the conference building (Irvine Building). The desk will remain open throughout the rest of the meeting. Name badges, programmes and abstracts volumes etc. will be distributed from this desk.

PRESENTATIONS

Presentations will take place in the appointed lecture theatre (Irvine Lecture Theatre, Irvine Building, no. 46 on map). Those presenting talks are politely requested to load their presentations onto the computer in the lecture theatre during the morning registration of Thursday (20th) or during the preceding refreshment/lunch break prior to their session. Presentations should be saved in Microsoft PowerPoint or PDF format only. Speakers have a 20 minute slot allocated in the timetable, and keynote speakers are allocated 40 minutes.

POSTERS

The posters will be on display in the Forbes Room of the Irvine Building. The formal poster session will take place on Thursday 20th March from 5.40-6.45 pm. Delegates are free to visit the posters at any time. Those presenting posters are encouraged to put them on display by lunchtime on Thursday (20th). Refreshment breaks will be held in this room and so there will be many opportunities for delegates to view your work. Posters can be a maximum size of A0, portrait in size.

NAME BADGES

Registered participants are required to display their name badges at all the scientific sessions during the meeting.

CONFERENCE DINNER AND CEILIDH

The Conference Dinner will take place on Thursday evening, 20th March, at 7.00 for 7.30 pm at the Lower College Hall (no. 44 on map). Dinner tickets are pre-booked and included in delegate packs where arranged. The Conference Ceilidh will take place in the Upper College Hall (no. 44 on map) from 9.30 until 11.30 pm. Tickets to the ceilidh are included in the price of the dinner. Delegates not attending the dinner, but wishing to attend the ceilidh later that evening can do so for an additional charge of £10 (payable on entry or at the registration desk). A bar will be serving drinks throughout the evening.

STUDENT BURSARIES

The Mineral Deposit Studies Group (MDSG) has generously provided funding for student bursaries. Students eligible for these funds are: Presenting students from UK/Ireland Universities, and/or non-presenting students who are members of MDSG (i.e. have attended the MDSG Conference). All students registered at NAC Conference, and eligible under these guidelines, are automatically entered for a student bursary. Eligible students should visit the registration desk to ensure that their names are on the list of those to receive funding. Monies will be paid by bank transfer after the conference.

MDSG and the NAC Conference organising committee will confirm the amount available per student during the conference.

KEYNOTE SPEAKERS

Keynote speakers sponsored by NAC Conference, should attend the registration desk to submit their receipts. Monies will be paid by bank transfer after the conference.

POST-CONFERENCE FIELD TRIP

The post-conference field trip to the Lewisian of NW Scotland will take place between Saturday 22nd and Wednesday 26th March. Delegates registered to attend this trip using the transport and accommodation organised by the NAC Conference, and additional field trip participants attending by their own transport, are required to attend a brief pre-field trip meeting during the conference. The time for this meeting will be announced during the conference. All field trip participants will receive a printed field guidebook with field localities and logistical information, including a schedule and contact numbers. The guidebooks will be distributed on the morning of departure for the field trip.

We intend to depart St Andrews at 8am on Saturday 22nd March. We will return on Wednesday 26th March via Inverness Airport, Perth and Leuchars Train Stations, and St Andrews. Where possible, this is to allow participants to make connections for further travel. We anticipate returning to St Andrews by 4pm.

Accommodation: All paying participants attending the field trip have been provided with hotel accommodation, with all meals included (breakfast, packed lunch and dinner). For information, these hotels include: The Old Inn at Gairloch, The Rhiconich Hotel, and The Tongue Hotel.

Participants attending the trip via their own means of transport are required to organise their own accommodation and meals.

Field equipment: The NW of Scotland in March can see very changeable weather. We advise that you bring many layers (allowing for a range of conditions from snow to sunshine) and cold- and wet-weather clothing, including hat, gloves, waterproof trousers, waterproof jacket, etc. You must bring sturdy footwear with good grip (walking boots).

Field trip participants requiring further information in advance of the conference are directed to Kathryn Goodenough (kmgo@bgs.ac.uk) and Hannah Hughes (HughesH6@cf.ac.uk).


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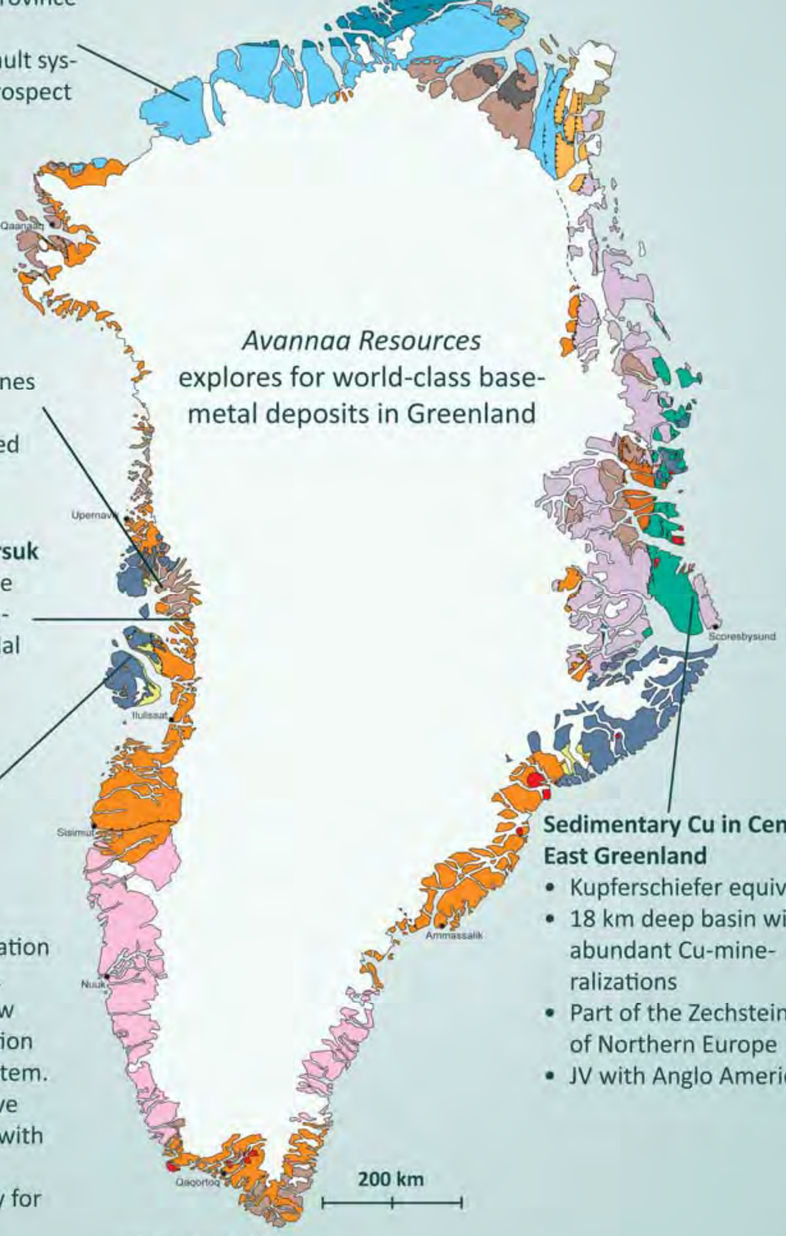

Map courtesy by GEUS

Sedimentary Cu in Central East Greenland
- Kupferschiefer equivalent
- 18 km deep basin with abundant Cu-mineralizations
- Part of the Zechstein Basin of Northern Europe
- JV with Anglo American

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Programme

19th March			
18.00	Icebreaker and registration opens ***(sponsored by Avannaa Resources)***		
	Venue: Parliament Hall, University of St Andrews		

20th March			
Session 1: Regional-scale controls and the geology of the NAC. Chair Prof Nicholas Arndt			
08.30	Registration *(Forbes Room, Irvine Building)*		
09.00	Welcome *(Irvine Lecture Theatre, Irvine Building)*		
09.20	Begg (Keynote)	p. 14	Cratonic structure and regional controls on mineral syste
10.00	Corrigan	p.15	The North Atlantic Craton and its bounding terranes in Canada: tectonic framework and mineral potential
10.20	Goodenough	p.16	Tectonic history and mineralisation in the North Atlantic Craton: A view from Scotland
10.40	Rollinson	p.17	The oxidation state of the Archaean mantle: insights from the precise measurement of $Fe^{3+}/\Sigma Fe$ in Archaean chromitites
11.00	Coffee *(Forbes Room)*		
11.30	Szilas	p.18	The geochemical composition of Archaean ultramafic, mafic and andesitic rocks of supracrustal and intrusive origins, SW Greenland - Geodynamic implications
11.50	Hamilton	p.19	Proterozoic mafic dyke swarms of the Western North Atlantic Craton: Distribution, age, geochemical and paleomagnetic studies, and implications for Precambrian plate reconstructions and metallogeny
12.10	Davies J	p.20	New insights on the evolution of the North Atlantic Craton from geochronology and isotope geochemistry of the Scourie dykes, NW Scotland.
12.30	Bartels	p.21	Geochemistry and U-Pb geochronology of mid-Proterozoic dyke swarms within the North Atlantic Craton, South Greenland
12.50	Lunch *(Forbes Room)*		
Session 2: Metallogeny of the NAC - general. Chair Dr Kathryn Goodenough			
14.00	Kolb (Keynote)	p.22	Metallogeny of the North Atlantic Craton, Greenland
14.40	Finch	p.23	How does nature make the perfect rare element deposit? Insights from the Gardar Province of Southern Greenland
15.00	Upton	p.24	Incompatible element concentration within in the Late Gardar Southern Rift, South Greenland
15.20	Tea *(Forbes Room)*		
16.00	Hunt	p.25	Peralkaline magmatic layering: development of the eudialyte-rich Unit 0 marker horizon, Ilimaussaq Complex, S. Greenland
16.20	Pandur	p.26	Apatite and allanite-hosted REE mineralization at Hoidas Lake, Saskatchewan, Canada and impications for the melts/fluids responsible for REE deposition and remobilization
16.40	Fagan	p.27	Initial thoughts on the geology of the Aappaluttoq Ruby Deposit
17.00	Hawkesworth (Keynote)	p.28	Mantle metasomatism and the continental record
17.40	Poster session and evening drinks *(Forbes Room, **sponsored by Northern Shield Resources & Midland Valley Exploration)***		
19.00	Dinner and Ceilidh *(Lower College Hall and Upper College Hall, **ceilidh sponsored by Northern Shield Resources)***		

21st March *(Irvine Lecture Theatre, Irvine Building)*

Session 3: Metallogeny of the NAC - layered intrusions and Ni-Cu-PGE. Chair Prof Judith Kinnaird

09.00	Barnes (Keynote)	p.29	Using the trace element contents of magmatic sulphide and oxide minerals in exploration for and exploitation of magmatic ore deposits.
09.40	Maier	p.30	Understanding layered intrusions and their ore deposits: still many rivers to cross
10.00	Arndt	p.31	Ni-Cu-PGE potential of the NAC
10.20	Bliss	p.32	Seeing the Forest for the Trees: Using Geochemistry as a Vector in PGE Exploration along the Eastern Margin of the Superior Province, Canada
10.40	Pattison	p.33	The Maniitsoq Ni-Cu-Co-PGE project, Qeqqata Kommunia, southern West Greenland
11.00	Coffee *(Forbes Rooms, **sponsored by Northern Shield Resources)***		
11.30	Gulbrandsen	p.34	The Disko Island, West Greenland, Noril'sk Type Ni-Cu-PGE target; geological settings and analogies to a world class nickel camp
11.50	Sabra	p.35	The Disko Island, West Greenland, Noril'sk Type Ni-Cu-PGE target; applied geophysical methods in deep and blink exploration targets
12.10	Hughes H	p.36	The potential for orthomagmatic Ni-Cu-PGE mineralisation in Western Scotland: observed controls and mechanims
12.30	Bowles	p.37	Freetown, a tear in the corner of the North Atlantic
12.50	Lunch *(Forbes Room)*		

Session 4: Metallogeny of the NAC - Gold & base metals. Chair Dr Adrian Finch

14.00	Goldfarb (Keynote)	p.38	Targeting orogenic gold: What are the keys for exploration?
14.40	Hughes J	p.39	Intrusion Related Gold Systems in South Greenland – The Proterozoic Nanortalik Gold Belt
15.00	Schlatter	p.40	Gold mineralisation & differences of associated hydrothermal alteration of Archaean gold prospects in SW Greenland
15.20	Charter	p.41	A review of the Gairloch Cu-Zn-Au Deposit
15.40	Davidheiser-Kroll	p.42	Fluid flow on the Iapetus Suture: Timing and composition
16.00	Coffee *(Forbes Room)*		

Session 5: Exploration techniques. Chair Dr Denis Schlatter.

16.20	Nicoll	p.43	The past is the key to the future: insight gained through thinking about projects in their geodynamic context
16.40	Davis T	p.44	Constraining margin evolution with basic structural techniques
17.00	Stove	p.45	Dragging exploration into the Quantum Age: using the ground penetrating abilities of a new coherent radiowave and microwave imaging spectrometer

Thanks to all NAC Conference's sponsors, including:

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Student bursaries available courtesy of The Mineral Deposits Studies Group

Poster presentations

Cratonic structure and regional controls on mineral systems

G.C. Begg[1,2*], J.M.A. Hronsky[3], S.Y. O'Reilly[1], W.L. Griffin[1] and Lev Natapov[1]

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[2]Minerals Targeting Intl., 17 Prowse St., W. Perth, WA 6005, Australia
[3] Western Mining Services (Aust.) Pty Ltd, 17 Prowse Street, W. Perth, WA 6005, Australia
*graham@mineralstargeting.com

Ore deposits are the outcome of a conjunction of factors including tectonic processes, melting processes, fluid and metal transport mechanisms, and metal accumulation processes. A commodity-fertile source region is generally an essential ingredient, and may be convecting mantle (e.g. Ni, Cu), metasomatised lithospheric mantle (e.g. Au, diamonds), lower crust rich in incompatible elements (e.g. Sn, W, U), or upper crustal rocks amenable to metal leaching by oxidised fluids (e.g. Cu, Pb, Zn, U). The physical framework that facilitates the above is supplied by the interaction of geodynamics and continents. More specifically, by the interplay of global dynamics (mantle convection, mantle plumes, plate tectonics) and the sub-continental lithospheric mantle (SCLM; e.g Griffin et al., 2013).

There are particular tectonic & lithospheric settings in which various types & styles of ore deposits are formed. These settings include:- intracratonic diamondiferous kimberlites; craton margin mafic-hosted Ni-Cu-PGE; pericratonic basin-hosted ultramafic Ni-Cu-PGE; craton flank-hosted layered intrusion (PGE, Fe-Ti-V); magmatic arc-related porphyry & epithermal metal (Cu-Mo-Ag-Au, Cu-Au, Sn-W, Au-Ag); oceanic back-arc VHMS (Cu-Zn-Pb-Au-Ag); inverted (pericontinental) rift back-arc orogenic (Au); continental retroarc porphyry, epithermal & iron oxide (Cu-Au-Mo, Au-Ag-Te); intracontinental basin sediment-hosted base metal (Ag-Pb-Zn, Cu-Co), active foreland MVT (Pb-Zn), continental basin (U); continental shelf BIF (Fe).

Old SCLM is bouyant relative to oceanic lithosphere, physically durable, and highly viscous. Its appearance in the Archean forced plate tectonics to re-organise, and resemble that which we see in the modern Earth. Subsequent interaction of global dynamics with the SCLM facilitated the appearance of the afore-mentioned tectonic & lithospheric settings, and most of the metal source regions. These same dynamics triggered ore formation in discrete episodes. None of the resultant deposits are preserved through tectonic cycles unless they reside over old buoyant SCLM, with those in intracontinental settings particularly favored. In contrast, the relatively dense oceanic lithospheric mantle is easily removed (subducted, delaminated) and associated deposits destroyed.

Our interpretation of multidisciplinary geoscientific data, coupled with geochronological (e.g. U-Pb on zircons) and isotopic investigations (Re-Os on SCLM mantle sulphides, Lu-Hf on zircons), indicate that approximately 70% or more of today's continental lithosphere formed between ca 3.6-3.0 Ga. The absence of significant mineral deposits older than about 3Ga is attributed to either of a failure to survive due to reworking (melting, thickening, thinning, erosion) of the crust, or to the absence of a key ore-forming factor. Plate tectonics (forces, fluids, magmas) has resulted in metasomatism, fracturing, melting and suturing of the SCLM into a continental mosaic. These processes, plus the impact of mantle plumes and the rise of atmospheric oxygen, have provided the metals, energy and focus for ore systems in a range of associated crustal environments.

REFERENCES:

Griffin, W.L., Begg, G.C. and O'Reilly, S.Y. (2013). Continental-root control on the genesis of magmatic ore deposits. **Nature Geoscience**. Vol. 6, pp. 905-910.

The North Atlantic Craton and its bounding terranes in Canada: tectonic framework and mineral potential

David Corrigan[1*] and Mary Sanborn-Barrie[1]

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The western edge of the North Atlantic Craton (NAC) is well exposed along the coast of Labrador in Canada where it has been historically referred to as the Nain 'Province' or 'Craton'. It is bounded by Paleoproterozoic age orogens; to the west by the 1.87-1.86 Ga Torngat Orogen, and to the south by the 1.89-1.80 Ga Makkovik (Ketilidian) Orogen. The Nain-NAC consists of two terranes or blocks (Hopedale and Saglek) that had independent histories prior to their Neoarchean amalgamation . The Hopedale block of southern Labrador (James et al., 2002) is a multiply-deformed greenschist- to amphibolite-facies granite-greenstone belt formed during the interval 3.3 to 2.8 Ga. The granulite-facies Saglek block of northern Labrador (Bridgwater and Schiotte, 1991) contains supracrustal and plutonic rocks as old as ca. 3.9 Ga, incorporated in predominantly metaplutonic crust of ca. 3.7 to 3.2 Ga age. The boundary between the Hopedale and Saglek blocks is obscured by Mesoproterozoic-age AMCG-type intrusions, including those hosting the Voisey's Bay Ni-Cu-PGE deposit and is interpreted as a ca. 2.55 Ga suture. Emplacement of the Mesoproterozoic suites may have been governed by far-field lithospheric-scale stresses linked to arc accretion on the (then) SE margin of Laurentia.

At the northern tip of Labrador (Burwell domain) and beyond on Baffin Island, the potential extent of the NAC is a matter of ongoing research and debate, with a number of tectonic models based on limited data being published over the last few years (e.g., Corrigan et al., 2009; St-Onge et al., 2009, among others). Refinements to the proposed models are emerging as current government-supported bedrock mapping programs and field studies come to fruition. Crustal age distributions, and continuity of geophysical lineaments and bounding Paleoproterozoic orogens, suggest that the Burwell domain and the southeastern tip of Baffin Island comprise NAC crust that was reactivated during the Paleoproterozoic-age Torngat and Trans-Hudson orogenies (Nagssugtoqidian). Further to the north, however, the boundary zone between the NAC and the Rae Craton is obscured by the Paleoproterozoic-age Piling Group and its equivalent on Greenland, the Karrat Group and by voluminous 1.89-1.84 Ga plutonic rocks.

New mapping on eastern Baffin Island (Cumberland Peninsula) has revealed a 2.99-2.93 Ga basement complex whose lack of ca. 2 Ga Kangâmiut mafic dyke equivalents together with maximum detrital and Nd model ages of 3.5 Ga, do not suggest NAC heritage. Rather, the presence of a voluminous belt of ca. 1.89 Ga plutonic rocks and establishment of penetrative tectonic interleaving of the basement complex with Paleoproterozoic cover rocks at ca. 1.86 Ga point to a potential upper-plate setting of an intervening crustal block (Aasiaat equivalent?), during NAC collision (Nagssuqtoqidian orogeny).

Recent field mapping combined with research and gold exploration programs on the Piling Group suggests that it may represent a Red Sea type proto-ocean basin opening towards the east, with implications for the nature and mineral potential of the Karrat Group. The various known mineral deposit types of the North Atlantic Craton and bounding terranes will be discussed in light of postulated tectonic settings.

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Bridgwater, D. and Schiotte, L. (1991) **Bulletin of the Geological Society of Denmark**. Vol. 39, pp. 153-166.
Corrigan, D., Pehrsson, S., Wodicka, N., and de Kemp, E. (2009) **Journal of the Geological Society of London**. Vol. 327, pp. 457-479.
James, D.T., Kamo, S. and Krogh, T. (2002) **Canadian Journal of Earth Sciences**. Vol. 39, pp. 687-710.
St-Onge, M.R., Van Gool, J.A.M., Garde, A.A., and Scott, D.J. (2009) **Journal of the Geological Society of London**. Vol. 318, pp. 193-235.

Tectonic history and mineralisation in the North Atlantic Craton: A view from Scotland

Goodenough, K.M.[1*], Macdonald, J.M.[2], Johnson, T.E.[3], Hughes, H.S.R.[4], Shaw, R.A.[5], & Millar, I.[6]

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[4]School of Earth and Ocean Sciences, Cardiff University, Park Place, Cardiff CF10 3AT, UK
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[6]NERC Isotope Geosciences Laboratory, Keyworth, Nottingham NG12 5GG, UK
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The Lewisian Gneiss Complex of North-west Scotland represents a c. 250 km x 150 km fragment of the North Atlantic Craton, comprising tonalite-trondhjemite-granodiorite (TTG) gneisses that were formed in the Archaean and successively reworked during the Palaeoproterozoic. This talk will review new work on the event history of the Lewisian, and its relationship to the wider North Atlantic Craton.

A significant programme of zircon dating over the last two decades showed that the protoliths of the Lewisian Gneiss Complex TTG gneisses were formed in the Archaean (c. 3100-2800 Ma) and that different protolith ages occur in different terranes within the Lewisian Gneiss Complex (Kinny et al., 2005). Similar relationships have been recognised in the Archaean gneisses of Greenland. However, most Lewisian gneisses are characterised by a 'smear' of zircon ages along concordia between c. 3000 and 2500 Ma, and it is difficult to disentangle protolith and metamorphic ages. Mafic to ultramafic rocks, and some supracrustals, are locally associated with the TTG gneisses; their ages are uncertain, but they may represent the remnants of Archaean greenstone belts.

Some relatively undeformed granitoids found within parts of the Lewisian Gneiss Complex give preliminary U-Pb zircon ages of c. 2800-2700 Ma. These granitoids may be related to the similarly-aged Skjoldungen alkaline province in East Greenland. The tectonics of the Lewisian at this time are uncertain. Field evidence clearly demonstrates that some parts of the Lewisian Gneiss Complex have undergone a granulite-facies metamorphic event, associated with extensive partial melting, known as the Badcallian. The age of this event remains controversial, but is generally considered as either c. 2800-2700 Ma (Corfu et al., 1994) or c. 2500 Ma (Kinny et al., 2005). In the North Atlantic Craton in Greenland, orogenic events have been recorded between c. 2860 and 2600 Ma, and were typically associated with gold mineralisation (Kolb et al., 2013).

Most workers in the area are agreed that a subsequent period of metamorphism and deformation, known as the Inverian, took place around c. 2480 Ma. This was followed by continental extension and the emplacement of mafic dyke swarms across the North Atlantic Craton, including the Scourie Dyke Swarm in the Lewisian Gneiss Complex. The magma source included components from the sub-continental lithospheric mantle that had been enriched by Archaean subduction-derived fluids.

The next major activity in the Lewisian Gneiss Complex occurred around 1900 Ma, as continental arcs developed along the margins of the North Atlantic Craton. In the Lewisian, these arcs are represented by sedimentary and volcanic rocks of the Loch Maree Group and South Harris Complex, as well as granitic intrusions into these and other major terrane boundaries. Stratiform sulphide deposits associated with the Loch Maree Group have been explored for Cu, Zn and Au. Subsequent deformation (the Laxfordian event) was associated with crustal thickening and partial melting, and emplacement of pegmatites between c. 1790 and 1660 Ma. These include some rare-metal pegmatites, with a compositional range between two end-members: a LREE-enriched end-member, and a Li-Ta-enriched end-member.

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Corfu, F., Heaman, L.M. & Rogers, G. (1994) **Contributions to Mineralogy and Petrology** Vol. 117, pp. 215-228
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The oxidation state of the Archaean mantle: insights from the precise measurement of $Fe^{3+}/\Sigma Fe$ in Archaean chromitites

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The oxidised nature of the Earth's upper mantle is at variance with the conditions required for equilibrium between the lower mantle and the Earth's core. This implies that at some stage in Earth history the upper mantle has been oxidised. This oxidation must have taken place after the formation of the core, but the precise timing is contested. Some authors argue that oxidation took place very early in Earth history during the latter stages of accretion [1]. Others have proposed that the rise of oxygen in the atmosphere marked by the Great Oxidation Event (GOE) at 2.3-2.4 Ga [2] reflects a mantle oxidation event.

Previous studies have used the trace element ratio V/Sc as a measure of mantle oxidation state back to 3.5 Ga [3] or Fe-isotope ratios as a proxy for the $Fe^{3+}/\Sigma Fe$ ratio of the mantle back to 2.7 Ga [4]. Here we present new results for the direct measurement of $Fe^{3+}/ \Sigma Fe$ ratios in mantle derived magmas back to 3.8 Ga. We have investigated $Fe^{3+}/$ Fe ratios in chromite in mafic and ultramafic magmas on the basis that chromite is the first phase to crystallise from the melt and so represents the $Fe^{3+}/\Sigma Fe$ ratio of the melt, which in turn is a function of the $Fe^{3+}/\Sigma Fe$ ratio of the mantle source. We have developed a new methodology for the accurate determination of Fe^{3+} in chrome spinels using a combination of electron probe microanalysis, Mossbauer spectroscopy and single crystal X-ray spectrometry. Our method currently provides the best approach for making precise measurements of $Fe^{3+}/\Sigma Fe$ ratios in chromitites from mantle derived melts [5].

We apply this new methodology to late Archaean chromitites from the ca 2.7 Ga Northern Marginal Zone of the Limpopo Belt in Zimbabwe, the ca 2.9 Ga Fiskenaesset complex of west Greenland and to early Archaean chromitites from the >3.8 Ga Ujaragssuit intrusion in west Greenland. Our petrological data suggest that the chromitites from Zimbabwe and from Ujaragssuit crystallised from komatiitic magmas, whereas the Fiskenaesset samples formed from an aluminous basalt. We have sought to isolate samples in which the chromite is in equilibrium only with melt and the mineral olivine in order to ensure that the Fe^{3+} partitioning is entirely between the chromite and melt phases. On this basis we compare our Archaean results with samples from the Proterozoic Bushveld complex and from the 95 Ma-old Oman ophiolite. All samples suites record a variety of oxidation states some of which are post magmatic. However, we observe no difference in the oxidation state of magmatic chromites over geological time, supporting the view that the oxidation of the Earth's upper mantle had taken place before 3.8 Ga. These findings are in agreement with previous studies using trace elements and Fe-isotopes as proxies and suggest that the oxidation of the Earth's atmosphere was not directly coupled to mantle processes. Further, it supports the emerging view that the GOE may have been more protracted than previously supposed [6].

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The geochemical composition of Archaean ultramafic, mafic and andesitic rocks of supracrustal and intrusive origins, SW Greenland - Geodynamic implications

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I present an overview of geochemical data produced during my research on Archaean ultramafic-mafic-andesitic rocks from SW Greenland, North Atlantic Craton. All of these rock assemblages share the common feature that they are intruded by (and thus predate) the regional orthogneisses, which currently host them.

Ultramafic serpentinites of the Mesoarchaean Tartoq Group consist of large slivers and enclaves (up to 100 x 2000 m), which form tectonic imbricates within mafic supracrustal rocks. A magmatic (komatiitic/boninitic/picritic) or residual mantle (MOR/forearc) origin for the protoliths of the serpentinites can be rejected based on their geochemical compositions. Fractionated platinum-group element (PGE) patterns suggest a magmatic cumulate origin and the normative mineralogy of their protolith is harzburgitic. Similar serpentinites from the Eoarchaean Isua supracrustal belt also display fractioned PGE's with two distinct geochemical trends of tholeiitic and boninitic affinity. The preferred interpretation of these serpentinites is an origin as olivine+chromite±orthopyroxene cumulates, which crystallised from the parental magmas of the associated mafic supracrustal magmas. Although these serpentinite data do not provide unambiguous evidence, we find many similarities with lower crustal ultramafic cumulates from the Mesozoic Kohistan and Talkeetna island arc sections.

Fresh dunite bodies (up to 500 x 1000 m) are associated with orthopyroxenites and norites in the Akia Terrane. Cumulus textures are obvious in the orthopyroxenites and norites and continuous layered chromitite bands (up to 20 cm thickness) are present at the margins of the dunites. Preliminary data with highly depleted olivine (Fo = 92.1-93.5) and spinel (Cr# = 13.1-65.3, Mg# = 33.3-91.4) compositions suggest that they represent cumulates derived from boninitic or crustally contaminated picritic magmas. The PGE patterns of the dunites display unusual negative anomalies for Rh, which may be related to mineralisation in the norites.

Mafic rocks of tholeiitic basalt composition comprise the majority of Archaean supracrustal belts in this region. They commonly have negative high field strength element anomalies, which together with their juvenile Hf- and Nd-isotope compositions, is taken as evidence of an island arc affinity.

Andesitic leucoamphibolites are only found in some of the supracrustal belts. Their geochemical compositions cannot be explained by fractionation from mafic tholeiitic basalts. Instead they show distinct mixing trends between ultramafic/mafic magmas and TTG-type crustal melts in roughly equal proportions. Their Hf- and Nd-isotope compositions suggest contamination with pre-existing continental crust, although some contributions are relatively juvenile and may thus represent slab-derived melts. It should be noted that similar magma mixing trends are observed for modern arc-related andesites and are explained by magma chamber assimilation processes.

In summary, the ultramafic rocks generally represent olivine+chromite±orthopyroxene cumulates derived from tholeiitic or boninitic magmas. The mafic greenschists and amphibolites mainly represent juvenile tholeiitic basalts, which commonly have arc-signatures. The andesitic leucoamphibolites represent products of mafic/ultramafic magma mixing with TTG-type felsic melts. Thus, the overall geochemical data, suggest that subduction zone geodynamic environments may explain the magmatic activity recorded by the Archaean rocks of SW Greenland.

Proterozoic Mafic Dyke Swarms of the Western North Atlantic Craton: Distribution, Age, Geochemical and Paleomagnetic Studies, and Implications for Precambrian Plate Reconstructions and Metallogeny

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The North Atlantic craton (NAC) is but one of nearly three dozen preserved Archean cratonic nuclei worldwide which each, together with their mantle roots, represent dispersed fragments of once larger landmasses – supercratons or supercontinents. Largely assembled by the late Archean, they often preserve peripherally a record of Paleoproterozoic sedimentary basin formation, passive margin development, or volcanic basins including oceanic lithosphere development now conserved within younger orogens.

Whether these cratons were initially assembled as part of a single late Archean supercraton, or as a small number of distinct, individual supercontinents remains a critical question that is central to our understanding of Archean and Proterozoic geodynamics (e.g. Bleeker, 2003). Investigating the ancestry of each cratonic block is a labour-intensive task, even in the best-exposed shield areas. However, the breakup history of the supercontinents has left a rich legacy of magmatic products in the form of large igneous provinces (LIPs), typically preserved as continental rift and flood basalts, basic dyke swarms that fed them, and layered mafic intrusions at various crustal levels. Often understudied, diabase or dolerite dyke swarms are unique and invaluable because it is likely that supercontinent breakup leaves a brief record of rifting or aborted rifting on adjacent blocks; landmasses with a long-lived nearest-neighbour relationship should preserve a record of a shared ‘magmatic barcode’ unique to that supercontinent. Dyke swarms offer piercing point constraints and offer the best opportunities for recovering robust paleomagnetic poles, essential for plate reconstructions. The most significant advance in recent years, however, has been our ability to recover rarer and smaller mineral phases in mafic dykes and date them with high precision by U-Pb methods.

We present new results describing the protracted history of extension and breakup of the western margin of the NAC, principally in the Labrador segment (Nain craton) and in southern west Greenland – blocks isolated since the onset of Mesozoic plate separation. Each region is shown to share a common, punctuated history of mafic magmatism throughout the Paleoproterozoic. The data strengthen our earlier conclusions, based upon precisely dated barcode matches at 2.5 Ga, 2.21-2.23 Ga, 2.14-2.12 Ga, 2.05-2.03 Ga and 1.95 Ga that the NAC lay proximal to the northeastern flank of Superior craton during this interval (e.g. Nilsson, 2012). Identification of 2.37 Ga dykes in south Greenland (Nilsson, 2012) presently represents a unique age match globally only with the Dharwar Giant Dyke Swarm (Dharwar craton; Halls et al. 2007; Kumar et al. 2012). NAC, Superior, Dharwar, and Slave cratons share a number of high-precision age matches for mafic dyke swarms that are being further investigated with geochemical and paleomagnetic studies of NAC dykes. The latter aims to establish the first key Paleoproterozoic paleopoles for the NAC and to test nearest neighbour relationships, cratonic affinity and supercraton paleogeographies at specific time intervals. LIPs linked with continental breakup are well-known drivers of ore mineralization, particularly as important primary hosts to orthomagmatic deposits of Ni-Cu-PGE, Fe-Ti-V oxide and chromite, but they can also influence a number of other deposit types (e.g. hydrothermal IOCG, VMS).

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New insights on the evolution of the North Atlantic Craton from geochronology and isotope geochemistry of the Scourie dykes, NW Scotland.

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The 'Scourie' dykes are a NNW-trending mafic/ultramafic dyke swarm that intrudes the Lewisian gneiss terrain (hereafter referred to as Lewisian) of Northwest Scotland. They represent important time markers in the evolution of the Lewisian as they intruded between two high-grade metamorphic events – the Inverian (~2.5 Ga) and the Laxfordian (~1.7 Ga). Importantly, the Laxfordian event in the area around Loch Assynt is expressed primarily as deformation and metamorphism along large shear zones, which acted as conduits for Laxfordian fluids and strain, rather than pervasive regional deformation. For this reason, the Scourie dykes in the area around Loch Assynt are much better preserved than in the surrounding areas and therefore provide important constraints on the Paleoproterozoic history of the Lewisian.

We present new U-Pb zircon and baddeleyite geochronology for 10 Scourie dykes that indicates the main episode of dyke emplacement occurred at ~2400 Ma with a duration lasting ~30 Ma. We also report a younger dyke age of ~2040 Ma which, combined with a previous U-Pb baddeleyite 1990 Ma age from the Strathan dyke (Heaman and Tarney, 1989) confirm the presence of multiple mafic dyke intrusion events in the Lewisian over ~400 Ma.

All of the dykes experienced a Pb-loss event that correlates with the timing of the Caledonian orogeny, possibly related to fluids generated by the development of the Moine thrust. Epidote, sericite, and chlorite are secondary minerals that occur within some dykes and provide direct evidence for post-emplacement fluid alteration. Oxygen isotopes from the Scourie dyke zircon indicate exchange with heavy $\delta^{18}O$ fluids, which we interpret to be Caledonian in age. Despite the fluid exchange, a combination of SIMS oxygen isotope analysis, trace element analysis and Raman spectroscopy can be used to pinpoint areas in the zircon, which contain the original oxygen isotopic signature. We present oxygen isotopic data, which indicate that some of the Scourie dyke zircons have very low primary $\delta^{18}O$ signatures (as low as -3‰), lower than most igneous zircons worldwide. So far, the low $\delta^{18}O$ signature is only present in the ~2400 dykes.

We combine the geochronological and geochemical data to suggest a model for the formation of the Scourie dykes and early Paleoproterozoic tectonic evolution of the Lewisian.

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Geochemistry and U-Pb geochronology of mid-Proterozoic dyke swarms within the North Atlantic Craton, South Greenland

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The mid-Proterozoic Gardar Igneous Province in South-West Greenland developed in a continental rift-related environment. Several alkaline intrusions and associated dyke swarms were emplaced in Archean and Ketilidian basement rocks during two main magmatic periods at 1300 – 1250 Ma and 1180 – 1140 Ma.

To constrain mantle source characteristics of the Gardar magmatism and a possible prolongation towards the North-East, Gardar mafic dyke swarms as well as mafic dykes from the Timmiarmiit area at the South-East coast of Greenland were investigated geochemically and geochronologically, using Fusion-ICP-MS and baddeleyite U-Pb TIMS, respectively.

In multi-element diagrams of incompatible elements, the oldest generation of dykes within the Gardar Igneous Province is characterized by enrichment of large ion lithophile and light rare earth elements and depletion of Th, U, Nb and Ta. In comparison, the rocks of the younger magmatic period are more alkaline, show a general more enriched character with less pronounced negative Nb-Ta anomalies and have significant positive anomalies for Ba and P. The dyke swarm in the Timmiarmiit area shows identical geochemical characteristics when compared to the oldest generation of Gardar dykes and yields similar U-Pb baddeleyite ages of 1275±2 to 1270±2 Ma.

These data indicate a time dependent compositional change within the Gardar magmatism, providing evidence for the involvement of two geochemically distinct mantle components. A first depleted source, re-enriched by fluid metasomatism and a second more enriched source possibly intermixed with phlogopite and apatite components.

The obtained U-Pb ages and geochemical data provide a potential link of the investigated mafic dykes from the Timmiarmiit area to the early Gardar magmatic period. Additionally, it strengthens the already hypothesized relation of the early Gardar magmatism to mafic dyke swarms in central Labrador (Nain and Harp swarm) providing new evidences for a much more wide spread magmatism. These observations offer new insights into rift-related magmatic events, prior to the break-up of the Nuna supercontinent.

Metallogeny of the North Atlantic Craton, Greenland

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The North Atlantic Craton (NAC) of Greenland, which is also exposed in parts of the coast of Labrador in the Nain Craton of Canada and the Lewisian Complex of northwestern Scotland is bound to the north, south and west by Palaeoproterozoic and in the east by Caledonian orogens. Before it's fragmentation, the craton would have had a triangular shape covering an area of ~200,000 km^2. The NAC in Greenland is composed of Eoarchaean to Neoarchaean rocks and subdivided into various different terranes based on different geological history and bounding shear zones. In spite of controversial discussions in the literature on Earth's geodynamic system in the Archaean, the NAC of Greenland is traditionally regarded as having been shaped by Archaen plate tectonic processes at least after ca. 3.2 Ga.

Eoarchaean (3.85-3.60 Ga) successions in southern West Greenland are divided into the Isua Greenstone Belt (IGB) and different gneiss complexes. The complexes record a complicated history of intrusion, deformation and metamorphism during the 3660-3540 Ma Amiitsoq Orogeny, and contain narrow bands of paragneiss and meta-volcanic rocks. The IGB hosts the ca. 3710 Ma Isua Deposit, which is an Algoma-type banded iron formation (BIF) with a resource of 1107 Mt at 32.6% Fe. The BIF consists of quartz-magnetite bands, minor grunerite-magnetite bands and a ~10 m wide siderite-magnetite band. The BIF is >2 km long and 180-450 m thick increasing down dip. The main ore is the quartz-magnetite BIF with <0.3 m thick magnetite bands. A second target of hematite-quartz BIF is located in drilling through the Inland Ice.

Late Palaeoarchaean to Mesoarchaean (ca. 3.25-2.80 Ga) units consist of tonalite-trondhjemite-granodiorite (TTG) and monzogranite orthogneiss, mafic-ultramafic complexes, and various narrow greenstone belts ranging in metamorphic grade from granulite to lower-greenschist facies in the southwest. The greenstone belts in the Nuuk area contain stratiform W and polymetallic massive sulfide occurrences, which are both interpreted as hydrothermal exhalative seafloor deposits. The Kvanefjord Amphibolite (Paamiut) and the Tartoq Group contain komatiite and ultramafic schist with local Ni occurrences, and the Tartoq Group includes narrow BIF units. Ultramafic intrusions in the Tasiusarsuaq Terrane and the Thrym Complex also host local Ni-sulphide mineralisation. The ca. 3.0 Ga Norite Belt in the Maniitsoq area hosts several massive and net-veined Ni-sulphide deposits in plugs and sheets in a 75 m long belt. The ore has a Ni tenor of 6-8% and additional Cu, PGE and Au credits. The ca. 2970 Ma Fiskenæsset Complex (FC) has an anorthosite-leucogabbro-gabbro-ultramafic rock association that forms concordant sheets of <2 km thickness and ~50 km long strike length. The complex hosts magmatic PGE mineralisation (<4 ppm) and a Cr deposit (100 Mt at 22.4% Cr). The chromite is Fe- and Al-rich with a Cr/Fe ratio of 0.85. The rocks have been metamorphosed at granulite facies, retrogressed at amphibolite facies, complexly folded, and intruded by granitoids with xenoliths of the FC. Chromitite layers are <20 m thick and concentrated in the anorthosite layers of the FC. The mafic to ultramafic rocks contain abundant hornblende and a geochemical signature that suggest melt source in metasomatised mantle and intrusion in a volcanic-arc setting.

Three major Mesoarchaean deformation events are recognised: the ~2950 Ma Isukasia Orogeny; the 2850-2830 Paamiut Orogeny; and the > 2790 Ma Timmiarmiut Orogeny. The Isukasia and Paamiut orogens host orogenic gold in shear zones cutting greenschist-lower amphibolite facies greenstone belts at Isua, Paamiut and Tartoq.

Neoarchaean (ca. 2.80-2.50 Ga) units include the < 2840 Ma Simiutat Supracrustal Belt (SSB), monzogranite and intrusions of the 2720-2650 Ma Skjoldungen Alkaline Province (SAP). The SSB hosts locally polymetallic massive sulphide occurrences in the Nuuk area, which are interpreted as VMS-type deposits metamorphosed at amphibolite-granulite facies conditions. The SAP is represented by a sequence of ultramafic to syenitic and carbonatitic intrusions in South-East Greenland, which host narrow igneous magnetite layers.

The NAC was finally amalgamated during the 2800-2700 Ma Tasiusarsuaq and Skjoldungen orogens and the 2650-2580 Ma Kapisilik Orogen. The Tasiusarsuaq Orogen hosts an orogenic gold occurrence at Sermilik and stockwork-veined Cu-Ag mineralisation at Ameralik, which may represent a porphyry-type mineralisation. The Kapisilik Orogen is characterised by orogenic gold mineralisation in its foreland. The Tasiusarsuaq Gold Province consists of several small occurrences of low grade, whereas the Godthåbsfjord Gold Province includes two current exploration targets in the Storø and Qussuk projects.

The generally deep erosion level of the NAC defines it's metal endowment and in particular mineralisation with liquid-magmatic Ni-PGE-Cr-Fe mineralisation forming in deeper crustal levels during construction stages of the crust, and orogenic Au occurrences forming during the destruction stages of the crust (orogeny). Mineralisation that formed at the surface, i.e. BIF, VMS and komatiite-hosted Ni, are restricted to greenschist facies areas at Isukasia and Tartoq, and tectonic slices in higher-metamorphic terranes.

How Does Nature Make the Perfect Rare Element Deposit? Insights from Alkaline Rocks of the Gardar Province of South Greenland

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Alkaline and peralkaline rocks constitute a very small volume of the Earth's crust and yet they host many of the world's most profitable rare element deposits, notably in Zr, Nb Ta and REE. These are often multi-element deposits, potentially partly insulated from the vagaries of prices in a single commodity. How do we find alkaline centres, what features to we look for regionally and locally when prospecting? How can late-stage fluid activity modify those rocks? Does fluid interaction improve the grade or reduce it?

The purpose of this talk is to consider what might constitute the perfect rare element deposit, and then to compare that ideal scenario with our experiences in the Gardar Province of South Greenland. The Gardar hosts a number of world-class rare element deposits including the Zr, Nb and REE-rich Kringlerne and Kvanefjeld deposits within the Ilimaussaq Complex, the REE & Ta mineralisation of Motzfeldt and V-Ti deposits in the Isortoq region. Why does the Gardar host such a range of deposit types and what lessons can be learned for other prospects elsewhere in the world?

We present new Lu-Hf isotope data in the Gardar that tell us about the ultimate provenance of HREE. We show how the Gardar magmatism tapped an unusual enriched mantle source and how fractionation led to the formation of alkaline and then peralkaline magma types. Finally late-stage hydrothermal alteration in many cases reduced the value of the deposit by altering the primary mineral of interest, and/or creating nm-scale intergrowths of minerals that are difficult to process. These are explored using Ilimaussaq and Motzfeldt as examples.

Incompatible element concentration within the Late Gardar southern rift, South Greenland

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Following the Ketildian orogeny (~2.0-1.80 Ga) the resultant Columbia supercontinent, as preserved in south Greenland, underwent extensional stresses and rifting, in two principal episodes, at ~1280 Ma and ~1160 Ma. Associated alkaline magmatism gave rise to the Gardar Alkaline Igneous Province. In the younger Gardar twin rifts developed within a 70 km wide belt inside the granitoid batholith that concluded the Ketilidian orogeny. The broader (25 km) Northern Rift lay along the northern boundary of the batholith whilst the narrower (10-15 km) Southern Rift lay along the batholith axis. Both rifts, eroded to depths of ~ 3-4 km, are principally defined by dyke-swarms, punctuated by central-type alkaline complexes, inferred to be sub-volcanic. Large-scale basaltic magmatism characterised both the Older & Younger Gardar events. Compositionally the basaltic magmas differed from the OIB-type basalts of typical continental rifts. Older and younger Gardar basalts share geochemical affinities in being transitional olivine basalts, with high Al/Ca ratios conferring general troctolitic compositions. Their high LILE and negative Nb anomalies in normalised plots indicate some subduction affinity believed to have been inherited from a subducting oceanic slab in the Ketilidian. These characteristics were retained within the lithospheric mantle for 500 to 700 Ma until accessed by Gardar rifting.

The Southern Rift is of particular interest. Not only do the basaltic compositions show distinctly lower HREE/LREE and Zr/Nb ratios but also a relative enrichment in P. The rift includes the Ilimaussaq Complex, largely composed of extremely enriched agpaitic rocks that make it the world's second largest potential REE source and the sixth largest potential U source. It is hypothesized that an asthenospheric wedge developed beneath the rift in the Later Gardar and that fluorine-rich small melt fractions carrying complex ions rising from it became focussed and enriched the lithospheric mantle from which the magmas originated.

Peralkaline magmatic layering: development of the eudialyte-rich Unit 0 marker horizon, Ilímaussaq Complex, S. Greenland

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The Ilímaussaq Complex, S. Greenland, contains some of the most evolved igneous rocks in the world and is considered as a substantial deposit of rare-earth elements, Ta, Nb and Zr. One of the places these elements are concentrated is in the Kakortokite Layered Series, on which our work focuses, where they are hosted within eudialyte. This series comprises 29 repetitive tripartite units, numbered -11 to +17 [1] relative to the Unit 0 marker horizon, which has one of the richest concentrations of eudialyte. Each unit is subdivided into layers through modal mineralogy: the lower layer is arfvedsonite-rich black kakortokite, the middle layer is eudialyte-rich red kakortokite and the upper layer is nepheline- and alkali feldspar-rich white kakortokite. Despite much work on the development of the Kakortokite Layered Series, no consensus on the physico-chemical processes that led to the formation of the rhythmic layering has been forthcoming, although most hypotheses suggest gravitational sorting and settling contributed to layer formation. We present a detailed petrographical, quantitative textural and mineral chemical study of samples from 4 locations across Unit 0, with the aim of defining the magmatic processes involved in the development of the unit. Crystal size distribution (CSD) analysis was performed on hand-digitised photomicrographs to give insight into processes of crystal nucleation and growth.

The sharp boundary from Unit -1 to Unit 0 is traceable across the entire complex, suggesting that large-scale magma chamber processes formed Units -1 and 0. The CSDs indicate pervasive textural coarsening affected each of the samples studied, masking the primary crystallisation features. Despite this it is inferred from the CSDs that multiple processes of crystallisation occurred, including *in situ* crystallisation, which we suggest was most effective during formation of the black and red kakortokites. Also processes of gravitational settling and crystal fractionation occurred, which are suggested to have been most effective during the development of the white kakortokite layer. The order of crystallisation is suggested to have been associated with changes in volatile pressure, this could have allowed for initial formation of arfvedsonite at high concentrations of volatiles [2], forming the black kakortokite. Above this layer eudialyte crystallised concentrating the ore elements in the red kakortokite. Decreasing volatile contents would allow for crystallisation of alkali feldspar and nepheline to form the top layer of white kakortokite. Chemical variations in Fe_{TOT}/Mn of eudialyte were additionally noted between the 3 layers of Unit 0, indicating they formed from an evolving magma. We use this in combination with the petrography to infer that Unit 0 formed in response to a replenishment event in an open-system magma chamber.

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Apatite and allanite-hosted REE mineralization at Hoidas Lake, Saskatchewan, Canada and implications for the melts/fluids responsible for REE deposition and remobilization

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A realization that hydrothermal processes have played a significant role in the formation of economic REE deposits has increased gradually in the past decades (e.g. Williams-Jones *et al.* 2012). The Hoidas Lake LREE-enriched veins provide a natural laboratory where such processes can be evaluated due to the absence of a direct magmatic source. The Hoidas Lake deposit is located in northern Saskatchewan, Canada and consists of hyalophane-bearing pegmatite dikes, diopside-allanite-(Ce)-hyalophane veins, fluorapatite breccia veins and late-stage quartz-carbonate veins, all of which cut the strongly deformed and metamorphosed Archean and Paleoproterozoic rocks of the southern Rae Province. The REE mineralization is closely related to the Hoidas-Nisikkatch Fault, which is considered a subsidiary of the regionally important Black Bay Fault system (Halpin, 2010).

Petrographic and electron microprobe analysis of the Hoidas Lake vein minerals were carried out to evaluate the chemical variations in the system, and to compare these to the results of fluid inclusion microthermometry and evaporate mound analysis. This allows us to constrain the evolution of fluids during the progression of the REE mineralization, and the effects of late hydrothermal fluids.

REE concentrations vary from 7 to 24 wt. % total rare earth oxides (TREO) in allanite crystals, and from 1 wt. % to 5.5 wt. % TREO in apatite crystals. These REE variations and the presence of oscillatory zoned allanite associated with late carbonate veins indicate repeated influxes of the mineralizing “fluid” into the vein system. Interaction with hydrothermal fluids resulted in hematite and chlorite alteration and precipitation of monazite and REE-Sr-carbonates. The dominant medium postulated to be responsible for the REE mineralization is most probably a REE-enriched pegmatitic melt, preserved in the form of graphic-like melt inclusions in the apatite breccia. Fluids preserved in the system as fluid inclusions (FIs) include four distinct fluid inclusion assemblages (FIAs): *type 1* carbonic FIs with 20-40 vol.% V_{CO2} at 0°C, *type 2* aqueous FIs with 90-100 vol.% V, *type 3* aqueous L-V-H FIs with 15 vol.% V, and *type 4* aqueous L-V FIs with 15-20 vol.% V at room temperature. The observed range for CO_2 homogenization temperature in *type 1* inclusions (3° to 31°C), and more restricted ranges within FIAs are interpreted to indicate transient pressure variations during entrapment of these fluids. The *type 3* and *type 4* inclusions have homogenization temperatures from 90° to 290°C and variable salinities (8 to 40 wt.% eq. NaCl). Based on evaporate mound SEM-EDS studies, the aqueous fluids are Na-Ca dominant with lesser but significant Sr, K, Ba, Mn, Fe, Mg, S and F.

The complex chemistry of the fluids present indicates that the Hoidas Lake mineralized veins were likely related to an unexposed carbonatitic magma, and the source pegmatitic melt was transported along the Hoidas-Nisikkatch Fault system. The mineralized veins formed due to rapid changes in pressure (0.5 to 2 kbars) and multiple influxes of REE-bearing fluids/melts. The related hydrothermal fluids included carbonic and mixed aqueous fluids, the latter responsible for the local redistribution of REEs. The mineralogical, textural and chemical similarities of the Hoidas Lake deposit to other REE showings, such as the REE-enriched veins of the Cnoc nan Cuilean Intrusion in the Loch Loyal Syenite Complex (Hughes et al., 2013, Walters et al., 2013) and the apatite-rich veins of the Visakhapatnam District in India (Choudhuri & Banerji, 1976), and similar chemical signatures of the host rocks (e.g. elevated Ba, Sr) indicate that the source of the REEs and the mineralizing melts/fluids might be similar in these areas. In addition, the presence of major, deeply-rooted fault zones in all these areas suggest that such faults might have played a role in the formation of these REE deposits.

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Initial thoughts on the Geology of the Aappaluttoq Ruby Deposit

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The gem corundum deposits of SW Greenland are unusual and have received little scientific attention to date. The Aappaluttoq deposit is located approximately 30 km southeast of Qeqertarsuatsiaat (Fiskenæsset) and about 120 km south of the capital, Nuuk.

The Aappaluttoq deposit is important because it is one of the largest defined gem corundum deposits in the world. Together with the wider Fiskenæsset Complex, there is potential in the area for a high value gem corundum district akin to those of SE Asia and East Africa. At present, the project is in the final stages of mine permitting and the Company hopes to be issued a full mining licence in 2014; this will enable the marketing of Greenland gemstones and the beginning of construction on the mine itself.

The gem deposits are hosted in the Archean aged (2970 Ma) (Polat *et al.*, 2010) Fiskenæsset Complex. This is a layered igneous intrusion that spans several hundred kilometres across the Bjornsund structural block, which is a fundamental part of the North Atlantic Craton (Windley and Garde, 2009). The Complex has been well studied (*e.g.*, Windley *et al.*, 1973; Myers, 1985; Polat *et al.*, 2010), but the majority of the previous work has focussed on the overall Complex rather than the mineralization hosted within it.

The Aappaluttoq deposit is part of the Middle Gabbro stratigraphic unit; specifically it lies along the boundary between meta-leucogabbro and meta-melanogabbro; each rock unit is distinctive in its mineralogy and structure. Ruby and pink sapphire mineralization occurs where these two units are in contact with ultramafic units. The relationship between these three rock units is under discussion, but results to date show that the ultramafic units are probably the source of chromium, which is required by the corundum crystals in order for them to express the desirable deep red to pink colouration. The main ore rock is a biotite-phlogopite-corundum-bearing metamorphic/metasomatic unit that lies adjacent to both a sapphirine unit and the meta-leucogabbro. This metasomatic unit has been sampled and gives a very high grade of red corundum and ruby. The secondary ore is a meta-leucogabbro which contains a high percentage of pink sapphire.

Regionally the Fiskenæsset Complex contains numerous sites where corundum has become concentrated. Several of these display gem deposit characteristics similar to Aappaluttoq; however, further exploration work is required to define the resources at each new site.

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Mantle metasomatism and the Continental Record

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Metasomatism is a metamorphic process by which the chemical composition of a rock is altered by the introduction and/or removal of chemical components as a result of the interaction of the rock with externally sourced fluids or melts. Many interpreted that definition to imply that the bulk composition of metasomatised rock depends on the minerals that formed during metasomatism, which in turn determine which elements are preferentially retained, and which are not. Formally metasomatism therefore differs from chemical enrichment in that the latter can typically be modelled by the bulk addition of a fluid or melt composition, with little interaction with the host rock. However metasomatism is widely used to describe the development of enriched mantle, and often the re-enrichment of mantle that has previously been depleted by melt extraction. Such arguments are often made on major element grounds, for example, some mantle xenoliths have several modal percent clinopyroxene and garnet in rocks with very high Mg number, indicating a degree of re-enrichment that would in turn have influenced the distribution of minor and trace elements. In other cases mantle metasomatism is invoked on the basis of unusual distributions of minor and trace elements, including H_2O and CO_2. One of the consequences can be the development of more fertile source regions for subsequent magmatism.

The direct record of mantle metasomatim is in xenoliths of upper mantle material brought to the surface in alkaline magmas and kimberlites. Archaean mantle is characterised by relatively low Al, Ca and Fe contents, and it differs from younger mantle material which tends to be more fertile in major element compositions. Mantle material of different ages is preserved within the continental lithosphere, and in many areas the age of the oldest material in the mantle lithosphere is similar to the age of stabilisation of the overlying crust. Much of the age information is from Os isotopes, since Re is highly incompatible during mantle melting and the Os isotope ratios of mantle rocks reflect when partial melting and melt extraction took place. Os depletion ages cluster into peaks of ages, as do zircons ages from crustal rocks, and there is considerable debate over the extent to which these reflect primary ages and hence periods of enhanced magmatic activity. We have argued that the peaks of ages within the crust reflect the preferential preservation of igneous rocks in periods of collision and the development of supercontinents. If the age of mantle preserved material is linked to the age of the overlying crust, similar arguments may apply.

Links between processes in the mantle lithosphere and the development of economically viable deposits, are most striking in the scavenging of precious minerals, such as diamond, in mantle derived magmas. In most cases the development of ore bodies involves the concentration of elements that are heterogeneously distributed in the mantle. A key step is the generation of magmas in the upper mantle to transfer elements into the crust where the element abundances can be further concentrated into economically viable deposits.

Using the trace element contents of magmatic sulphide and oxide minerals in exploration for and exploitation of magmatic ore deposits.

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Over the past 15 years the development of laser ablation ICP-MS analysis has made it possible to determine the concentrations of trace elements in minerals down to the ppb level. This information has been used by the academic community to address petrogenetic problems. However, trace element contents can also be used in exploration for and exploitation of ore deposits. At LabMaTer, Universite du Quebec a Chicoutimi we specialize in determining trace element contents of magmatic sulphide and oxide minerals. Our approach consists of studying well characterized type examples of each ore type by: considering the texture of the minerals; determining the whole rock composition, and determining the trace element content of the minerals. Combining all of the data makes it possible to carry out a mass balance and deduce which mineral is controlling which element and try to deduce which process was important in the controlling each element.

The results of our studies could be applied to less well known samples, to heavy mineral separates from till or stream samples and to the evaluation of extraction efficiencies. For example the trace element contents of chromites from the mantle, boninites, komatiites, MORB, layered intrusions and OIB are different; with incompatible element concentrations increasing from mantle chromites to OIB chromites. Interestingly chromites from volcanic rocks contain the platinum-group elements (PGE) Ru and Rh, whereas the layered intrusion chromites do not. For Fe-oxides it is possible to distinguish magnetites from layered intrusions, anorthosites, granites, magmatic sulphides deposits, hydrothermal deposits etc.

Trace element contents of sulphide minerals are particularly important in exploitation of Ni and PGE deposits because the PGE may be present either in the sulfide minerals or as platinum-group minerals (PGM). Efficient extraction requires an understanding of which minerals contain each of the PGE. We have found that in most deposits 20-40 % of the Pd is present in pentlandite with the balance in PGM. Almost all of the Pt is present as PGM, although some can be present in pyrite. Rhodium is mainly present in pyrrhotite, pentlandite and pyrite. Osmium, Ir and Ru are present in pentlandite and pyrrhotite. Chalcopyrite contains very little of the PGE budget. Sulphide minerals do not survive transport very well. But if any pyrite is present in a heavy mineral separate and the pyrite contains Rh and or Pt this would be a good indicator of the presence of a nearby Ni or PGE deposit. Similarly if pentlandite or pyrrhotite are present and they contain Os, Ir, Ru, Rh and, in the case of pentlandite, Pd this is a positive sign for a Ni or PGE deposit.

Understanding layered intrusions and their ore deposits: still many rivers to cross

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Layered intrusions have been central in the development of many fundamental petrological ideas, including fractionational crystallization, crystal settling and gravitative fractionation, assimilation-fractional crystallization, density currents, double diffusive convection, etc. However, despite of more than 100 years of petrological research many aspect of their formation remain unclear, including the origin of layering in general, and that of anorthosites, chromitites, magnetites and PGE-bearing layers in particular, but also the nature of the parental magmas and their mantle sources, the role of contamination during ascent, and the tectonic setting of magmatism (e.g., compressive vs extensional). Mining companies have assayed 100s of thousands of samples and drilled 1000s of boreholes to define the extent and grade of the reefs, but much remains to be learnt about the origin of the ores, as illustrated by new discoveries even in mature ore fields such as the Bushveld Complex. New analytical tools now offer the possibility to make significant progress in understanding the petrogenesis of the intrusions. High resolution visualization tools, such as FESEM and X-ray fluorescence microscopy can provide improved insight into, e.g., the role of mixing and sorting of crystal mushes in the formation of cumulate layers, including the reefs. Of critical importance would be that the huge amount of data on layered intrusions and their deposits, largely resting within private company databases, can be compiled and evaluated by networks of researchers and industrial/public partners, to identify key ore forming criteria and produce GIS based prospectivity maps that can be used in targeting.

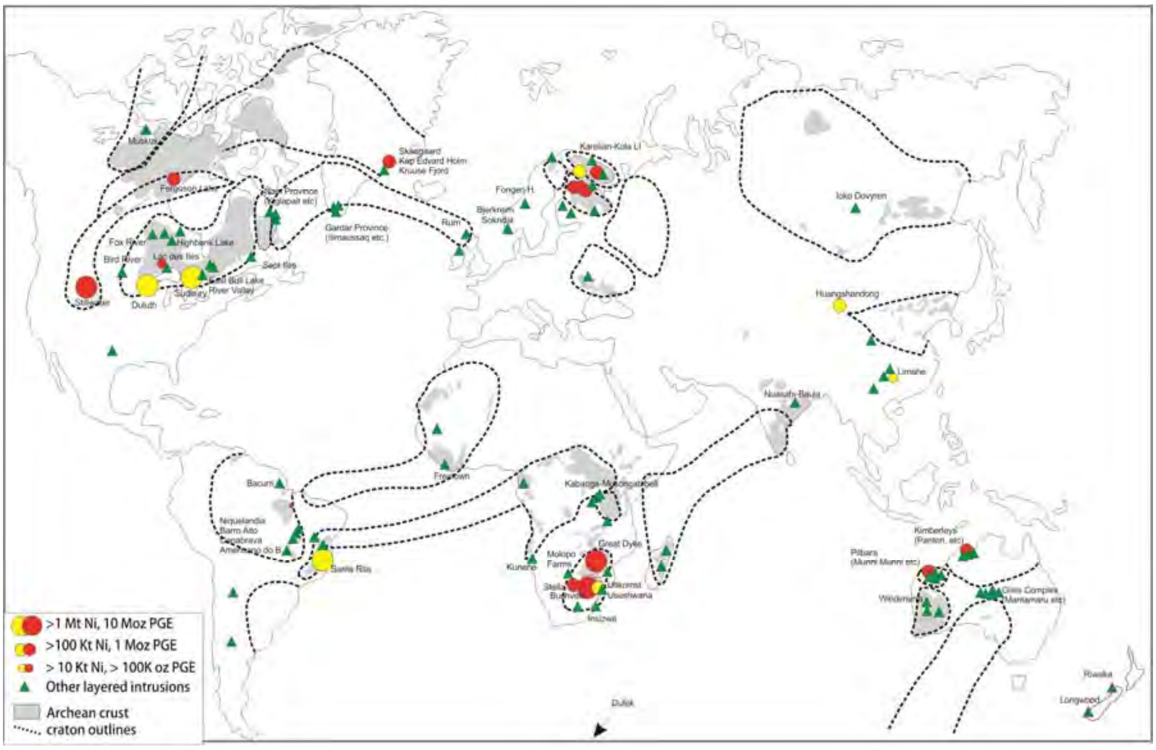

Fig. 1: Location of layered intrusions globally (modified after Maier and Groves, 2011)

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Ni-Cu-PGE potential of the NAC

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The North Atlantic Magmatic Province contains all the features that normally would qualify it as highly prospective for Ni-Cu-PGE deposits. Olivine-rich picrites are present and these magmas interacted with crustal rocks during their passage to the surface. The earliest lavas of the province erupted at ca. 62 Ma in West Greenland and 55 Ma in East Greenland as continental flood volcanics and these were followed by the emplacement of rift-related lavas during the opening of the North Atlantic ocean. Although the magmatic was protracted, extending to the present day in Iceland, the main eruptions of flood basalts occurred in short periods. As in most large igneous provinces, basalt is the dominant rock type but all sequences also contain highly magnesian picrites. There is abundant geological, petrographic and geochemical evidence that these magmas interacted with crustal rocks during their passage to the surface. The eruptions occurred as the margins of the Archean craton, a location favourable for the formation of Ni-sulfide deposits. New determinations of the MgO contents of the pricrites and their eruption temperatures from Coogan et al (2014) and our unpublished results indicate that the picrites comprise some of the hottest magmas that formed during the Phanerozoic, equivalent to the temperatures of Gorgona komatiites.

To our knowledge, no viable deposits of Ni sulphides have been found associated with the North Atlantic Magmatic Province. Lightfoot and Keays (2006) note that the volume of erupted lavas is relatively small, compared with the much larger volume of basalts and picrites in the ore-bearing Norilsk-Talnakh region, and they suggest that “the Greenland system is small and segregation of sulphide took place at high levels in the crust, whereas at Noril’sk, the saturation event took place at depth with subsequent emplacement of sulphide-bearing magmas into high levels of the crust." If this is true, there is a paradox because if the source were hot enough to generate very hot magmas, it should also have produced large volumes of low-degree basaltic magmas. In addition, the volume of picrite – the magmas that host the ore deposits at Norilsk – is relatively low and it is not evident that large volumes of this type of magma are a requisite for the formation of ore deposits. A possible solution might be found in the architecture of the lithosphere and crust, which could have limited the volume of basaltic magma that reached the surface.

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Seeing the Forest for the Trees: Using Geochemistry as a Vector in PGE Exploration along the Eastern Margin of the Superior Province, Canada

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Northern Shield's Idefix Property is located 75 km to the northwest of Kuujjuaq, in the Nunavik region of the province of Quebec. Significant PGE mineralization has been identified on the property by Northern Shield during exploration in 2012 and 2013 and three different styles are observed: (i) reef-type, (ii) hybrid reef-contact type and (iii) irregularly distributed globules of sulphide.

The gabbroic sill that is host to the PGE mineralization is found within a mafic-ultramafic sequence identified as being part of the Montagnais Sills. The Montagnais Sills are interpreted to be contemporaneous and comagmatic with associated volcanic rocks of the Kaniapiscau Supergroup in the Labrador Trough. The Labrador Trough forms the western margin of the Paleoproterozoic New Quebec Orogen, southeastern Churchill Province, which is the final result of the oblique collision between the Archean North Atlantic (Nain) and Superior cratons during the Trans-Hudson Orogen between 1.82-1.77 Ga.

Geochemical analysis and interpretation of over 900 mafic and ultramafic intrusive rock samples from Montagnais Sills collected in 2012 provided a better understanding of the magmatic events within the Labrador Trough. Based on geochemical differentiation, at least two distinct phases of gabbroic intrusions have been identified. The "Regional" gabbro defined in the study is generally not significantly mineralized in PGE with a few rare exceptions. The better PGE results are consistently found in the "Idefix-type" gabbro. This understanding has allowed Northern Shield to focus exploration work on areas where Idefix-type gabbro is found.

At the Idefix Property, the host sill is about 600 metres thick, and dips 60° to the east. Both Cr/V and MgO trends throughout the sill indicate that the intrusive stratigraphic sequence at Idefix is overturned. The sill appears to be part of a fractionated mafic-ultramafic event with the stratigraphically lower Primitive Sequence consisting of medium to fine-grained melagabbro(norite), olivine melagabbronorite and pyroxenite. The Idefix unit, dominantly consisting of gabbro, stratigraphically overlies the Primitive Sequence and is interpreted to represent a new pulse of magma into the sill. It tapers from 100 metres thick in the north to 60 metres at the south end of Idefix Ridge. The Idefix unit can be subdivided into the Lower, Upper and the Roof sub-units, though the latter may be a third unit of its own. The Roof sub-unit is in contact with sedimentary rocks dominated by shales, mudstones and quartzites with occasional cubic pyrite.

All eleven of the drill-holes completed by Northern Shield in 2013 along the Idefix Ridge and covering a strike length of over two kilometre show that the main PGE mineralization at Idefix is located at the interface of the Primitive and Idefix units. The mineralization is considered reef-type based on its lateral continuity and stratiform nature at the contact between distinct geological phases. The reef ranges in thickness from about 20 metres to 14 metres with grades ranging from 0.26 to 0.4 g/t Pt+Pd+Au over those widths. Unfortunately, the magma in the Idefix Ridge area likely cooled relatively quickly, preventing reef concentration processes from running to completion. The result is a thick, low-grade PGE-bearing reef.

At the La Colline showing, 800 metres south of the Idefix Ridge, surface sampling has identified a mineralized zone averaging 1.4 g/t Pt+Pd+Au, 0.28% Cu and 0.1% Ni over a width of 31.4 metres. Initial interpretation indicates that the mineralization at La Colline occurs at the same stratigraphic level as the reef along the Idefix Ridge. However, at La Colline, this PGE mineralized zone is adjacent to the contact with the country rock.

Globules of sulphide several centimetres in diameter are also seen in drill core and on surface. The globules, consisting dominantly of pyrrhotite with chalcopyrite rims suggest the existence of a pool of sulphide liquid prior to the pulse of magma that formed the Idefix unit. The globule-bearing gabbro contains up to 16 g/t Pt+Pd+Au and indicates another mineralization target at Idefix.

The Maniitsoq Ni-Cu-Co-PGE project, Qeqqata Kommunia, southern West Greenland

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The Maniitsoq project is situated on the southwest coast of Greenland and is 100% owned by North American Nickel Inc. (NAN). It covers an area of 3601 km^2 and is roughly centred on a 75 x 15 km curvilinear belt of nickeliferous norite intrusions known as the Greenland norite belt (GNB).

Recently the Maniitsoq area was identified as an ancient (3 Ga), deeply eroded, giant meteorite impact site (Garde, 2010). The centre of the impact is believed to be a 35 by 50 km comminuted zone referred to as the Finnefjeld Domain. The GNB norites are interpreted to represent crustally contaminated mantle melts triggered by the impact (Garde et al. 2012, 2013) and appear to have been emplaced in a magma conduit system that followed deep seated structures that remained active until as recently as the Jurassic when the Qeqertaasaq carbonatite complex was emplaced on the margin of the Finnefjeld Domain.

The norites are virtually undeformed and occur as plugs, dykes and elongated bodies exposed in outcrop over areas up to 8 km^2. They are hosted by well-foliated to locally cataclastic Mesoarchean quartzo-feldspathic orthogneisses and amphibolites (volcanosedimentary rocks that are often sulphidic). The norite intrusions typically contain abundant xenoliths of country rock and their contacts are often diffuse and hybridised.

NAN initiated the Maniitsoq project in 2011 because it believed that new technologies, such as h elicopter and borehole time domain electromagnetic systems, would be successful in locating and delineating magmatic sulphides associated with the norites. To date, the company has flown 6663 line-kilometres of helicopter TEM surveys and drilled 34 holes totaling 5817 m. Numerous mineralised zones have been intersected and many targets remain to be tested. So far, the best results have come from a cluster of three norite intrusions situated in the northern part of the GNB, collectively referred to as the Imiak Hill Conduit Complex (IHCC). Some significant intersections from the IHCC are listed in the Table 1.

Table 1: Selected NAN intersections in the Imiak Hill Conduit Complex.

Intrusion	Hole #	From (m)	To (m)	Length* (m)	Ni (%)	Cu (%)	Co (%)	TPM** (g/t)
Imiak Hill	MQ-13-026	149.81	175.32	25.51	3.25	0.48	0.11	0.01
	Including	156.70	175.32	18.62	4.31	0.62	0.14	0.01
Imiak North	MQ-13-029	57.75	113.50	55.75	1.28	0.36	0.04	0.06
	Including	103.51	113.50	9.99	4.65	0.33	0.13	0.14
Spotty Hill	MQ-12-005	41.36	165.30	123.94	0.81	0.21	0.03	0.26
	Including	117.80	142.00	24.20	1.75	0.34	0.06	0.52

* Length is core length not true width **TPM = Pt+Pd+Au

All the mineralized zones in the IHCC remain open and NAN intends to conduct further drilling in 2014 aimed at determining their size. Drilling will also be done to test high priority electromagnetic conductors associated with norite intrusions throughout the Maniitsoq project area.

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The Disko Island, West Greenland, Noril'sk Type Ni-Cu-PGE Target; geological settings and analogies to a world class Nickel camp

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The West Greenland Palaeogene Igneous Province is one of the world's major continental flood basalt provinces and is characterized by a high proportion of Mg-rich, picritic rocks and a significant volume of sediment-contaminated lavas, many of which are depleted in Ni, Cu and PGE (platinum group elements) relative to uncontaminated rocks at comparable Mg# [Mg/(Mg + Fe2+)]. Contamination with S-rich, Cretaceous-Palaeoecene sediments in sub volcanic magma chambers is considered to have led to sulphide saturation and segregation of immiscible, Ni-Cu-PGE-enriched sulphide melt at depth, thus causing the observed chalcophile-element-depletion in extruded lavas.
Nickeliferous (up to 7% Ni, 4% Cu and 2 ppm PGE in ore) sulphide mineralisations in exposed intrusions testify to the operation of this process. Similarities with the Noril'sk region in Russia, has prompted extensive exploration for Ni-Cu-PGE mineralisations in West Greenland and mass balance calculations suggest 10^7-10^8 tons of Ni and comparable amounts of Cu trapped at depth in the sub-volcanic plumbing system.

In 2012, Avannaa Resources acquired the licences that have previously been explored by Cominco, Falconbridge, and Vismand Exploration. These earlier programs recognised the presence of deep targets but failed to test them due to technical problems with drilling. Avannaa is conducting a two-year work program to fully prepare for deep-drill testing in 2015.

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The Disko Island, West Greenland, Noril'sk Type Ni-Cu-PGE Target; applied geophysical methods in deep and blind exploration targets

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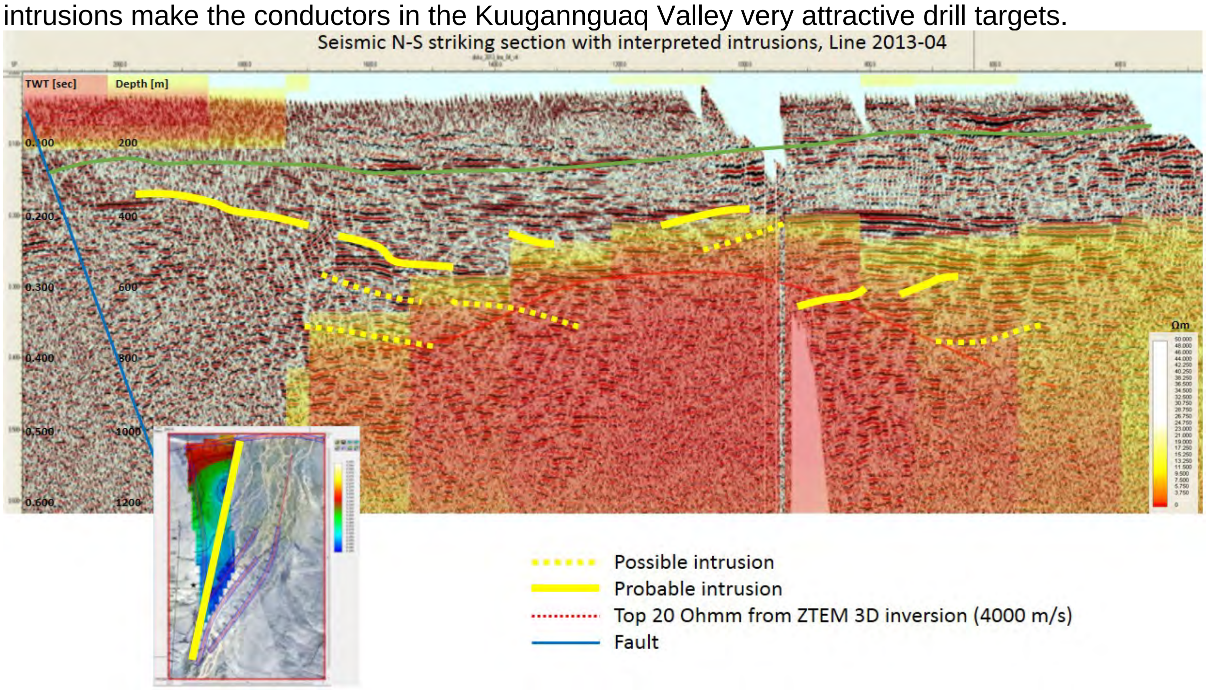
Perpetuation of "The Disko Island, West Greenland, Noril'sk Type Ni-Co-PGE Target – geological settings and analogies to a world class Nickel camp" by Pelle Gulbrandsen.

During 2012, Avannaa conducted 826 line km of airborne magneto-telluric (ZTEM) and magnetic surveys, followed by a pilot reflection seismic survey. The ZTEM results complement and extend historical Titan24 and other electromagnetic (EM) surveys and identify three conductive bodies beneath the Kuugannguaq Valley. The 2013 season included a 12.5 km high-resolution vibro-seismic survey covering the northernmost conductive anomaly, named José.
The UBC-GIF 3D inverted ZTEM data enhances a series of coherent and slightly sigmoidal-shaped conductors. The conductive bodies seem to emanate from a depth of 1000-1200 m's adjoining to the regional N–S fracture zones and gently rise towards southeast and east to a maximum burial of c. 500 m below surface. The three main conductive bodies all have a distinctly tubular shape with a height-width ratio of 1:2 to 1:3 and maximum widths of 700-1000 m. Lengths of the conductors range from 4-6 km but may well be restricted by the eastern extend of the ZTEM survey area. The seismic profiles across José show presence of high-amplitude discordant reflectors interpreted as intrusions at equivalent depths as the observed ZTEM conductors.

The appearance of the conductors José, Plácido and Luciano are consistent with the exploration model of mineralised sills at depth. The demonstration of a strong correlation between the conductive body and intrusions make the conductors in the Kuugannguaq Valley very attractive drill targets.



*Seismic line 2013-04 with possible (**dashed yellow lines**) and probable (**solid yellow lines**) intrusion interpretation. North is to the left and south to the right. Base of Neogene valley infill shown by **green line**. The 3D inverted conductivity is superimposed on the seismic section. **Yellow to orange shades** indicate conductivity of 10–20 Ωm, **red shade** less than 1 Ωm. Shallow conductor in the northern part of the profile probably represents saline water infiltrating from the Vaigat strait.*

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The potential for orthomagmatic Ni-Cu-PGE mineralisation in Western Scotland: observed controls and mechanims

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In recent literature, the apparent strong correlation between plume magmatism, Archaean cratonic lithosphere (particularly at the margins) and orthomagmatic Ni-Cu-PGE sulphide deposits has been highlighted (e.g., [1,2]). Although the reasons for this correlation remain contentious [3], this may be a reflection of some physical or chemical interaction between ascending asthenospheric plume magmas, and partial melts derived from a region of the subcontinental lithospheric mantle (SCLM). This desirable combination of plume magmatism intruding through an Archaean cratonic region exists in Western Scotland, where the British Palaeogene Igneous Province (BPIP; part of the North Atlantic Igneous Province) has intruded into a segment of the North Atlantic Craton (NAC; Lewisian in Scotland). Evidence of an enriched lithospheric keel below Western Scotland at the margin of the NAC, has been found in the form of Cu-Au-Pt-Pd enriched spinel lherzolite mantle xenoliths, which highlight a considerable elevation in the concentration of these elements in comparison to 'Primitive Mantle' at similar MgO contents (see Hughes et al. abstract, this volume). Additionally the Palaeoproterozoic Scourie Dyke Swarm highlights the magmatic contributions of the metasomatised SCLM keel to widespread melting events [4]. Due to the similarities in geological history between the NAC-portion of Greenland and Western Scotland, and considering the known Greenlandic Ni-Cu-PGE mineralisation, the BPIP is potentially the most prospective PGE province in Western Europe. This research focuses on the Scottish sector of the BPIP and also includes Caledonian (subduction-related) magmatics of this region. Thus the temporal and spatial abundances of PGE can be used to understand the mineralisation controls for orthomagmatic deposits here.

Powdered whole-rock grab samples were subjected to ICP-OES and ICP-MS analysis for major and trace elements, and NiS fire assay with ICP-MS finish to determine PGE and Au abundances. A selection of samples underwent S-isotope analysis via conventional (following whole-rock S extraction) and laser combustion (for larger sulphide minerals) methodologies.

The overall 'prospectivity' of the BPIP can be established by bulk geochemical analysis of volcanics from this area, particularly using the abundance of chalcophile elements in silicate lavas (e.g., Cu). By comparison to similar volcanics in Greenland, we find that both S-saturated and -undersaturated volcanics are found in the BPIP. This suggests that S-saturation has been achieved prior to the eruption of these lavas, hinting at the possibility of mineralisation lower down in the magmatic plumbing system. Whole-rock S-isotope analyses of minor and shallow-level intrusives indicate that S-saturation was achieved following substantial contamination of magmas by crustally derived S, with a characteristically light isotopic signature (e.g., basaltic dykes recorded on the Isle of Skye with S compositions as light as $^{\delta 34}S = -30.7‰$). Elsewhere on the Isle of Rum, ultramafic volcanic plugs can be found to contain abundant late-magmatic sulphides (pentlandite, chalcopyrite, pyrrhotite) with $^{\delta 34}S = -14.8‰$, and for which the S-isotopic signature and abundance of sulphides are directly correlated to the abundance of platinum group minerals (various Pt-Pd-Ir-As-Sb-Te-Bi minerals) and therefore PGE grade. By correlating the likely S-rich crustal contaminants (Jurassic mudrocks) across the Hebridean Basin, a mechanism by which late-magmatic PGM-bearing sulphides accumulated and 'slumped' during volcanic plug cessation can be envisaged.

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Freetown, a tear in the corner of the North Atlantic

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The North Atlantic opened first, beginning off the North African coast at about 200 Ma, the South Atlantic opened later starting at about 140 Ma. While southern Africa and South America remained attached, the North Atlantic opened slowly initially at about ~0.8 cm/yr north of latitude 9°N leaving a series of approximately E-W transform faults or fracture zones in the central Atlantic. Where the fracture zones meet the continental edge there is rifting parallel to the continental edge. By the North African coast these rifts are filled by igneous rocks giving rise to a magnetic anomaly (the West African Coast Magnetic Anomaly or WACMA). Off West Africa, the intersection of the fracture zones and the rifts created depressions filled by Cretaceous and later sediments of present interest to the oil industry.

The Freetown Layered Complex forms a peninsular jutting out into the Atlantic on the coast of Sierra Leone. On land, a layered sequence up to 7 km in thickness is exposed, dipping to the west. The rocks are formed of olivine, plagioclase and clinopyroxene that vary in proportion to create cyclic units. Certain cyclic units have been shown to contain elevated platinum-group (PGE) element concentrations and platinum-group minerals (PGM) have been identified in four horizons. A complete cyclic unit has troctolites at the base passing upwards through pyroxene troctolites, troctolitic gabbro, olivine gabbro, gabbro to leucogabbro and anorthosite at the top. Few units are complete as the upper and lower parts are often missing. Overall there is little progressive variation in silicate compositions indicative of magmatic fractionation, instead the cycles are repeated to form four major zones each containing numerous cycles. Petrographic, isotopic and geochemical evidence suggest that the intrusion is the result of repeated injections of magma. The petrographic evidence relies on the development of the cyclic units and the isotopic evidence on Rb-Sr and Nd-Sm studies. The development of PGM-bearing horizons having different Pd/Cu ratios indicates input of magma pulses differing in geochemistry. The intrusion was emplaced at 193 Ma.

The Guinea Fracture Zone reaches the continental edge at 9°N where the continental shelf is relatively narrow. There is rifting parallel to the continental edge continuing the WACMA to the south. The magnetic and gravity anomalies of the Freetown intrusion extend seawards to the west and north suggesting further layered units comparable in thickness to those seen on land. Interpretation of the northwards extension indicates that the intrusion dips below later sediments and is present to depths of at least 20 km. The orientation of the complete intrusion parallels the rifting of the continental edge, and the intrusion and the rifts both meet the Guinea Fracture Zone at 9°N. It seems likely that the Guinea Fracture Zone and the rifting provided a feeder conduit for the Freetown intrusion that remained open during the slow initial opening of the North Atlantic allowing repeated injections of magma. Those magma pulses came from a large body of magma that did not fractionate. In the context of the current meeting on mineralisation in the North Atlantic Craton, it is interesting to compare those layered intrusions in the north that result from a single injection of magma with the Freetown Intrusion that was the result of a continuous magma input over a prolonged period. The style of magma input depends on location.

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Targeting Orogenic Gold: What are the Keys for Exploration?

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Exploration targeting for orogenic gold, whether in a craton or a Cordilleran-style orogenic belt is readily based on a few key parameters. Such targeting is an essential first step in defining permissive tracts with high gold resource potential, which typically occupy much less than one percent of the area being investigated. Whereas many workers continue to debate gold source, fluid conduits and traps for gold deposition are well accepted. These features are determined through recognition of regional structure, metamorphic setting, and physical/chemical rock contrasts, and knowledge of such is essential in predicting where to spend your exploration dollars.

Most orogenic gold deposits are associated with first-order, crustal-scale faults that are essential for focusing fluid flow. Without such, a region may have many small deposits associated with less significant structures, but lack world-class orebodies. The large faults are typically thrusts that mark sutures between converging blocks or terranes. Reactivation of these faults some tens of millions of years after their initial formation, typically as transpressional to transtensional fault zones during periods of late orogenic uplift, corresponds to seismic events and major hydrothermal fluid flow events. Areas of jogs or greatest structural complexity along a regional fault zone are preferred sites of focused flow.

Greenschist facies rocks host the vast majority of the world's orogenic gold deposits and thus definition of metamorphic setting along a regional fault system is essential for exploration. The gold deposits are almost always formed post-peak metamorphism of their host rocks and thus on a retrograde P-T path. In a few cases, however, perhaps reflecting multiple metamorphic events, large Archean gold deposits have been metamorphosed at amphibolite and higher grades. Physical traps for gold ores in the metamorphic rocks are represented by rheology contrasts, such as a competent intrusion within a sequence of metasedimentary rocks. Chemical traps would include rocks rich in Fe/(Fe+Mg) or in carbon. Geophysical techniques may be useful in defining such favorable geology in areas of extensive cover.

Once favorable tracts for orogenic gold are defined using these criteria, exploration geochemistry should consider consistent pathfinders for ore that include As, Sb, Te, and W. Extensive areas of bleaching (sericitization), sulfidization, and particularly carbonization are important indicators of hydrothermal events associated with deposition of orogenic gold. A fore-arc or back-arc tectonic setting, the abundance or absence of spatially/temporally associated magmatism, and the presence or absence of a fertilized subcontinental lithospheric mantle are not consistent indicators of a high or low prospectivity for orogenic gold.

Intrusion Related Gold Systems in South Greenland – The Proterozoic The Palaeoproterozoic Nanortalik Gold Belt – a previously unrecognised Intrusion Related Gold System (IRGS) Province in South Greenland

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The highly underexplored >150 kilometre, Nanortalik Gold Belt (NGB) corresponds to the southern margin of the Paleoproterozoic Julianehåb Batholith (JB), with the Psammite Zone (deformed metasediments and lesser volcanics) to the southeast. Boundary structures are usually steep. The JB represents the central part of the Ketilidian Orogen which evolved during oblique northward subduction (sinistral transpression) of an oceanic plate under the southern margin of the North Atlantic Craton. The JB is dominated by a multi-phase, continental calc-alkaline batholith emplaced between 1850 and 1795 Ma. Regional deformation comprises of several large scale NNE- or NE-trending, sinistral syn-magmatic shear zones cross cutting the batholith. The NGB hosts Nalunaq in SW Greenland, Greenland's first producing gold mine (mined 2004 – 2013; estimated 9 tonnes of gold produced). Nalunaq is a narrow (0.5-2 metre wide) shear zone-hosted, exceptionally high-grade gold deposit (e.g. 5240 ppm gold over 0.8 metres) within hydrothermally altered metavolcanic rocks, with abundant visible gold (VG) in quartz (Kaltoft *et al*., 2000). Previous explorers in the region had neglected to realise the gold mineralisation potential of the granitiods (notwithstanding the presence of unexplained gold anomalies); their focus had always been limited, directed by the setting of the Nalunaq gold deposit. Recent exploration by NunaMinerals A/S within the Niaqornaarsuk Peninsula (the company's 435 km^2 Vagar exploration licence) has successfully applied an Intrusion Related Gold Systems (IRGS) model to the NGB, supported by recent petrological and lithogeochemical studies (Schlatter *et al*., 2013). Reappraisal of geochemical data from Nalunaq also supports the involvement of granitic intrusions in the introduction of the gold (Schlatter and Kolb, 2011). Sediment sampling within the Niaqornaarsuk Peninsula (approximately 25 kilometres north of Nalunaq) defines several large, highly anomalous gold clusters. The >3 x 4 km Greater Amphibolite Ridge (GAR) cluster hosts the strongest sediment gold anomalies in the whole of Greenland. Here quartz veins have yielded up to 2533 ppm gold. Channel sampling perpendicular to the auriferous 'Vein 2' structure at GAR during 2013 returned up to 13 meters at 70.1 ppm gold, with all profiles terminating in high grade gold mineralisation. Diamond drilling and channel sampling has established that the variably sulphidised (expressed as pyrite and pyrrhotite in patches and stockwork-like fine stringers) and silicified host granitoids (mainly granodiorites, subordinate granites) are gold mineralised commonly returning >1 ppm gold. Limited drilling to date (totalling 1916 meters) has revealed wide intersections of gold mineralisation, e.g. up to 79 metres at 0.96 ppm gold (including 23.3 metres at 2.47 ppm). Down dip continuity to >300 metres is indicated. VG has been observed in drillcore, channel samples and surface rock sampling. Several characteristics of the gold mineralisation conform to IRGS, including: 1) widespread gold mineralisation of granitic rocks; 2) elevated tungsten, bismuth and tellurium associated with the gold zones (including the presence of bismuth tellurides); 3) sericite, K-feldspar and carbonate alteration proximal to the mineralisation; 4) the gold mineralised granitoids have intruded into existing quartz diorites, gabbros and felsic volcanics; the contact zones are an important locus for gold. This is inferred to be a roof zone as defined by Hart (2007) in models derived from the Tintina Gold Province of the northern North American Cordillera. The contrast between gold mineralisation of the Niaqornaarsuk Peninsula and Nalunaq highlights the presence of differing deposit styles within the same district, a typical feature of IRGS (Hart, 2007). The identification of mineralisation conforming to IRGS criteria opens up large areas for investigation and marks a significant paradigm shift in Greenlandic gold exploration. Gold occurrences discovered along the continuation of the NGB in SE Greenland (the company's 370 km^2 Hugin exploration licence) demonstrate the significant district-scale potential of this gold play. Reconnaissance sampling at Jokum's Shear, near Danell Fjord has yielded up to 3.1 metres at 9.3 ppm gold from intensely silicified and sulphidised plutonic rocks. An NI 43-101 Technical Report on the Vagar Gold Project is available to be downloaded on the company's website: http://www.nunaminerals.com.

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Gold mineralisation and differences of associated hydrothermal alteration of Archaean gold prospects in southwestern Greenland

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The North Atlantic Craton of southwestern Greenland comprises Archaean terrane metamorphosed to greenschist and amphibolite facies and hosts several gold occurrences that are interpreted to be of orogenic type and to have formed between ca. 2850 Ma and 2610 Ma (Kolb et al., 2013). Here we compare the hydrothermal alteration associated with gold mineralization of ***Qussuk*** (Akia terrane), ***Qilanngaarsuit*** (Færingehavn terrane), ***Bjørnesund West*** (Tasiusarsuaq terrane) and ***Nuuluk*** (Sermiligaarsuk block). These gold prospects are located inland and near the southwestern Greenland coast and the distances between the northernmost (Qussuk) to the southernmost prospect (Nuuluk) is about 370 km. These gold occurrences are located in narrow greenstone belts which in turn are hosted in terranes largely dominated by TTG gneiss. The level of exploration is relatively low with Qussuk, and Nuuluk being drill tested whereas the others are only at grass roots exploration level. Gold at *Qussuk* is associated with pyrrhotite, chalcopyrite, biotite, muscovite and quartz and hydrothermal alteration is characterized by gains and losses of Na_2O+CaO and gains of K_2O+FeO+SiO_2 (Schlatter and Christensen, 2010). The *Qilanngaarsuit* Au zones are associated with garnet, plagioclase, quartz, biotite, sillimanite and sulphides and ore fluids were enriched in SiO_2, K_2O, LREE, Au, Cr, Cu, Zn, Mo and As (Koppelberg et al. 2013). At *Bjørnesund West* alteration is of garnet, biotite and iron oxide-hydroxide type and alteration is characterized by gains of FeO, SiO_2, CaO, As, Sb and Zn (Schlatter and Stensgaard, 2013). *Nuuluk* is different from the previously discussed prospects because intense and wide Fe-carbonate alteration occurs. During alteration K_2O, CO_2, FeO and SiO_2 have been added together with losses and gains of Na_2O. Up to 65 wt % of CO_2 was added and probably was an important component of the hydrothermal fluid (Schlatter et al., 2011). "Self-organizing map" methods were applied to the Nuuluk data and it is revealed that gold is associated with As, Sb, Cu, Ag, Cs, W and Bi.

It is shown here that regardless that gold in all studied prospects is hosted in quartz and/or altered meta-volcanic rocks and schist, alteration shows considerable differences and this is possibly related to chemical differences of the fluids that were associated with the introduction of gold. For example the extensive carbonate alteration seen at Nuuluk probably reflects that CO_2 was an important component of the hydrothermal fluid (Schlatter et al., 2011).

It is also seen that irrespective of the host rocks, the best gold mineralized prospects (Qussuk, and Nuuluk) are the ones where largest total mass losses and gains together with addition of FeO are seen.

The reason of the differences seen in the alteration styles of the studied gold prospects possibly can be explained by differences in their geotectonic setting, emplacement of gold at different crustal levels at different orogenic stages and differences in metamorphic grades. Recognizing a favourable alteration style associated with gold mineralization can help to focus gold exploration and to prioritize targets.

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A review of the Gairloch Cu-Zn-Au Deposit

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Gairloch is a partially explored copper-zinc-gold deposit, located on the NW coast of Scotland, located some 75 miles to the west of Inverness. The discovery outcrop was first described by C.T. Clough (Peach *et al*., 1907). The mineralization is hosted within the NW-SE trending Loch Maree Group, which consists of a variety of metasedimentary rocks interbanded with amphibolites that are considered to be of volcanic origin (Park, 2002). The depositional age of the Loch Maree Group is considered to be Palaeoproterozoic, around 2.0 Ga in age (O'Nions *et al*. 1983; and Whitehouse *et al*. 1997, 2001), bounded to the NE and SW by older highly deformed Archaean granodiorite gneisses.

Within the Kerrysdale amphibolite, two sulphide horizons have been identified, one pyritic, extending along strike for about 6km; and the other copper bearing, containing pyrite, pyrrhotite, chalcopyrite, sphalerite and native gold, extending along strike for about 1km (Jones *et al*, 1987). The style of mineralization is considered to be exhalative, and together with the presence of quartzite bands (metacherts ?) and striped magnetite quartzites (banded iron formation) strongly suggests a volcanogenic exhalative system, with similarities to well-known greenstone belt type mineralization.

From 1977 and 1983 Gairloch was explored by Consolidated Gold Fields Limited (latterly together with Outokumpu), who drilled 87 holes totalling 10,130m (Jones *et al*, 1987). A 'drill indicated and inferred' mineral resource has subsequently been estimated to contain 1.5Mt at an average grade of 1.8% copper, 0.6% zinc and 1.1 g/t gold. The mineralization, which has been modelled by Glasmin, is steeply dipping to the north at 75 to 80 deg. Structurally the mineralization appears to be confined to a block within two thrust planes, the Main Upper Thrust and the lower Western Basal Thrust, both pitching to the SE, and has been identified down to a depth of 400m below surface.

Between 1993-97, under the UK Government DTI-funded Mineral Reconnaissance Programme, the BGS carried out exploration in the Flowerdale Forest, located along strike and some 8km to the SE of the Gairloch Deposit. The BGS reported that "the succession at Loch Gorme na Beinne is similar to that at Gairloch and the presence of sulphide bearing banded iron formations (quartz magnetite schists) with significant gold values (up to 4 g/t) is highly prospective". Much of this area is obscured by overlying Torridonian Sandstones, with inlier 'windows' into the underlying Loch Maree Group.

Geochemical anomalies, related to the unusually high levels of Ni, Cu, Zn, V and Mg associated with the Loch Maree Group, are reported to extend further SE beneath the Moine nappe, as relatively high levels of first row transition elements are recorded in a zone extending SE along the Loch Maree fault, in both Moine metasediments and also the Lewisian area of Scardroy (Johnstone *et al*., 1979).

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Fluid flow on the Iapetus Suture: Timing and composition

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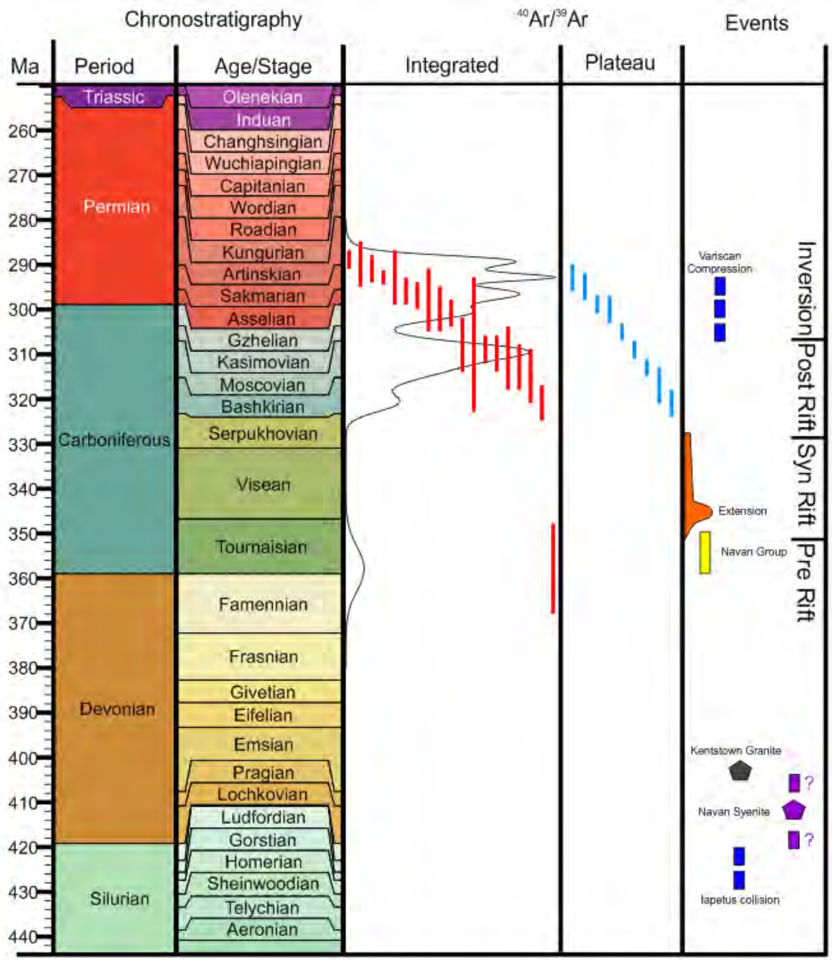
The timing of Variscan compression in central Ireland, and thus the inversion of the Navan Ore body, is poorly constrained. We have studied fragments of K-feldspar that display patch perthite textures from a syenite intrusion adjacent to the orebody in order to constrain the fluid composition and the age of local compression and inversion. Using $^{40}Ar/^{39}Ar$ geochronology we have constrained the timing of the most recent high temperature (300°C) fluid at 310-289 Ma, which we associate with the timing of local Variscan compression. Because the Ar system has not been completely reset, the age spectra obtained are complex and are thought to represent a hybrid age that is a function of both the intrusion age and at least the most recent episode of high temperature fluid flow. Modelling with DIFFARG, based on the emplacement age of the host syenite (ca. 400 Ma), age spectra obtained here, and the diffusion of Ar in K-feldspar, will better constrain the fluid timing (Wheeler 1996).



Patch perthite is not a magmatic texture but rather is thought to be produced by a fluid front passing through a feldspar crystal (Worden et al. 1990). To characterize the altering fluid we have analyzed $\delta^{18}O$ (8.3‰, n=3) in the feldspars and δD (-50 to -60‰, n=4) in lattice-bound water. Data show that the alteration of feldspars that resulted in the partial resetting of the Ar system involved fluids which were equilibrated with the basement at around 300°C. This is a much higher temperature than the local vitrinite reflectance measurements suggest, implying that the fluid was focused and flowed along major faults.

One feldspar grain yielded an integrated age similar to the likely timing of ore genesis for Navan and thus may have retained the relict age from this large-scale fluid event. $\delta^{18}O$ and δD analyses require multiple grains, thus the possibility that this results from distinct fluid signatures cannot be assessed. Hot fluids were clearly able to use the Navan syenite as a conduit at ~310 Ma during Variscan compression, causing inversion, and were also likely able to do so during the ore forming event at Navan.

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The past is the key to the future: insight gained through thinking about projects in their geodynamic context

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As major mineral discoveries are becoming harder to find, with fewer expressed at the surface, miners are increasingly being driven deeper into the subsurface and into more remote regions. This exposes companies and investors to much greater geological uncertainty and financial risk. Exploration companies increasingly need to think temporally and spatially to have a better understanding of regional geology, deposit models and drivers of mineralisation in order to explore for deeper and/or lower grade deposits.

The exploration and mining industry can however benefit from the huge geoscience research budgets spent by the hydrocarbon sector who have been exploring 'blind deposits' and thinking along these lines for a long time. Some of their well-developed techniques for project generation and regional understanding can be directly applied to aid mineral exploration. This presentation illustrates the power of such integrated thinking for understanding when and where mineral deposits formed. We highlight, through the use of our sophisticated and industry-leading global plate tectonic model, the distribution of mineral deposits through time and their intimate connection with differing tectonic environments.

Figure 1: present day distribution of Gold, Copper and Iron deposits along with a reconstruction showing the deposits that were forming in the Upper Devonian. (All images © Neftex)

We investigate and track volcanic arc activity, subducting margins, major collisional and inversion events, large igneous intrusive events and the Phanerozoic redistribution of mineral-rich Archean terranes through time. By compiling and integrating vast amounts of public data within a geodynamic framework what rapidly emerges is a fundamental understanding of the spatial distribution and geodynamic context of known mineral deposits through time. Such analysis can guide new exploration strategies and highlight where to go (in time and space) and what to expect, (in terms of tonnage and grade), when you get there.

Constraining margin evolution with basic structural techniques

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The magma-rich, rifted margin of the east coast of Greenland is well studied with respect to deep crustal seismic refraction data and is often used in analogue models to demonstrate the tectonic evolution of passive continental margins. Continental margin evolution is important in understanding rifting and better constraining arc collision events. Many of the current geophysical interpretations across east Greenland have not been validated by kinematic modelling.

Here we present the preliminary results of combined geological mapping, structural seismic features from other margins and structural techniques to try and better constrain one seismic refraction line (AWI-20030300) that is a widely used example of crustal rifting of a magma rich passive margin. Comparing features within this margin against those of better studied margins and their corresponding evolutional models allows for a first glimpse into the margin evolution constrained within a number of possible end member interpretations.

The east coast of Greenland margin separated from the coast of Norway during the Mesozoic, with rifting starting in the Jurassic. Aerial volcanic and plutonic rocks exposed along the margin are Palaeogene in age, much younger than many of the syn-rift sediments, and are generally flat lying. The Atlantic margin shows a mixture of basement fabrics, ages and trends. The study area lies within the easterly-directed Caledonian thrust belt that consists of large nappes that were reactived as detachments. These structures strike subparallel to the existing margin. The basement rocks in the study are a thick sequence of Precambrian sediments that are interpreted as an extremely thick shallowing sequence of continental margin sediments.

The study area was mapped using satellite imagery. Syn-rift sedimentation, fault throw estimates and an exhumed Neoproterozoic basement allows for estimates of timing and extension rate within the margin before magma intrusion and basaltic volcanism.
This study is intended to provide a good example of structural restoration and why constraining a number of plausible geological models with simple geometrics in one area can give a more constrained and broader understanding of timing, extension and structural style.

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Dragging Exploration into the Quantum Age: using the ground penetrating abilities of a new coherent radiowave and microwave imaging spectrometer

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The early use of Synthetic Aperture Radar (SAR) and LIDAR systems from aircraft and space shuttles revealed the ability of the signals to penetrate the ground surface. Atomic Dielectric Resonance (ADR) technology was developed as an improvement over SAR and Ground Penetrating Radar (GPR) to achieve deeper penetration of the earth's subsurface, through the creation and use of a novel type of coherent beam. When pulsed electromagnetic radio-waves pass through a material they generate measurable responses in terms of energy, frequency and phase relationships.

Atomic Dielectric Resonance (ADR) is a patented investigative technique (Stove, 2005) which involves the measurement and interpretation of resonant energy responses of natural or synthetic materials to the interaction of pulsed electromagnetic radio-waves, micro-waves, millimetric or sub-millimetric radio-waves from materials which permit the applied energy to pass through the material. The resonant energy response can be measured in terms of energy, frequency and phase relationships. The precision with which the process can be measured helps define the unique interactive atomic or molecular response behaviour of any specific material, according to the energy bandwidth used. ADR is measurable on a very wide range of hierarchical scales both in time and space. Time scales may range from seconds to femtoseconds, and spatial scales from metres to nanometres. In recent years, the technology for the production of laser light has become widely available, and applications of this medium to the examination of materials are constantly expanding. Whereas the earlier applications concentrated on the use of visible laser light, the development of systems using invisible laser light are now being further explored. Maser beams are well known. They are coherent beams of electromagnetic waves at microwave and radio frequencies. They are the longer wavelength equivalent of lasers.

In this contribution we wish to report on a series of experiments and fieldwork in which rocks of different compositions and textures have been exposed to pulsed beams of wideband, maser light conditioned dielectric resonance, to produce a range of differing atomic dielectric energy and frequency responses detectable by suitable receivers. Conditioning the beam by dielectric optics creates a synthetic lens effect so that the sensors appear to have much longer chambers with wider apertures than their actual physical size. This effect produces narrow coherent beams of pulsed and mased radio waves and microwaves which are good for illuminating target interfaces and materials. ADR transmit signals are within the high frequency radar to millimetre radar frequency range and have wavelengths of less than 100m.

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The Amikoq PGE deposit – tectonic fragments of an Archaean layered mafic intrusion in the Fiskefjord region, southern West Greenland

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Map-scale fragments of a layered mafic intrusion are dispersed throughout the Fiskefjord region of southern West Greenland. A chain of fragments defines the Amikoq complex, where the layered mafics occur between a basement of TTG gneisses and a roof of foliated amphibolites. The mafics comprise sheets with thicknesses up to 150 m and are distributed around a north-south oriented, 25 km long ‘keel’ in which the east and west sides mirror one another. This structure is broadly compatible with the dome-and-basin architecture of the Fiskefjord region. Scree sampling in the region by NunaMinerals A/S in 2006–2007 returned significant Pt+Pd concentrations around Amikoq. In a joint venture with Impala Platinum Holdings Ltd in 2008–2009, two PGE reefs were identified and characterised by *in situ* point sampling, channel sampling and diamond coring.

The igneous stratigraphy is dominated by leuconorites interlayered with pegmatoidal feldspathic pyroxenites and ultramafic lenses consisting of peridotites and dunites with occasional chromite seams. It is not clear whether these are related to similar ultramafic bodies in the roof amphibolites and basement gneisses. Igneous layering has a moderate to very steep westward dip throughout Amikoq, except where folded. Later east-west faults offset the Amikoq stratigraphy.

In the west, the basement and roof contacts are sheared at high metamorphic grade. Asymmetric folds indicate up-to-northeast vergence. By contrast, in the northeast the roof contact is a primary intrusive feature. In the southeast the basement contact is less tectonised than in the west, and in the south virtually no shear is observed along the basement or roof contacts. At least two areas in the east display large-scale tight to isoclinal folds with steep axes. Thus, strain may be partitioned between predominant contraction in the west and lateral shear in the east. Despite the intensity of deformation and metamorphism, igneous layering is largely preserved.

In the west, a 2–4 m thick PGE reef occurs in the basal layers of a leuconoritic package, has been traced for approximately 2.5 km, is open-ended and in places possibly repeated by folding. In the far south, a <0.5 m thick reef occurs at the base of a layered package of pegmatoidal feldspathic pyroxenites, is traceable along 500 m and is faulted out at its north and south limits. A peculiar feature of the southern reef is a chondrite-normalised PGE curve with a peak at Rh. Scanning electron microscopy of platinum group minerals (PGM) in four of the most PGE-enriched samples from the western and southern reefs shows the PGM to be extremely small and frequently associated with tiny sulphides (Fisher 2009). Metal ratios are highly variable and gold almost absent, probably indicating extensive modification of the original mineralisation by high-grade metamorphism.

Well developed zircons are common in the pegmatoidal pyroxenites, and two zircon ages from the north and south overlap within error at 2.95–3.03 Ga (Nilsson *et al.* 2010; Nutman 2009). The textural relationships of the zircons require further study in order to ascertain whether they represent the age of the Amikoq mafic intrusion or a younger magmatic event.

Chondrite-normalised PGE patterns, Mg numbers and Cr concentrations in different areas of the Amikoq complex reveal that at least the west and south represent very different levels of an original intrusive body or separate intrusions, although they are visually identical. The south is characterised by a relatively primitive mafic composition whereas the west is shown to be remarkably evolved. A smaller dataset for other parts of Amikoq suggests most of them are more akin to the south. The west is therefore anomalous. Data for Amikoq-style mafic fragments elsewhere in the region are insufficient to place them in context. North of Fiskefjord the layered mafics are more deformed and often micaceous, possibly reflecting slightly different histories across the major Fiskefjord Fault.

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Towie, Aberdeenshire, Scotland, GreenOre Gold Plc

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GreenOre Gold Plc "GreenOre" is an exploration company focused on developing minerals within the Scottish-Irish gold hosted 'Dalradian Supergroup'. In 2013 GreenOre was awarded a Mine's Royal Option Agreement for gold and silver in an area near Towie, Aberdeenshire, Scotland. The area was identified from arsenic anomalies, commonly associated with gold, in stream sediment samples collected by the British Geological Survey (BGS) in the 1980's and historical work conducted by Navan Resources in the 1990's. During 2013 GreenOre carried out various geochemical surveys to confirm and enhance the gold target at Towie. During this time further gold anomalies were found along strike from the mineralised 'Rhynie Fault Zone'. Rhynie is a well-known low grade epithermal gold system located 15km north of Towie. The latest results indicate various gold bearing structures at surface.

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A review of the Gairloch Cu-Zn-Au Deposit

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Gairloch is a partially explored copper-zinc-gold deposit, located on the NW coast of Scotland, located some 75 miles to the west of Inverness. The discovery outcrop was first described by C.T. Clough (Peach *et al*., 1907). The mineralization is hosted within the NW-SE trending Loch Maree Group, which consists of a variety of metasedimentary rocks interbanded with amphibolites that are considered to be of volcanic origin (Park, 2002). The depositional age of the Loch Maree Group is considered to be Palaeoproterozoic, around 2.0 Ga in age (O'Nions *et al*. 1983; and Whitehouse *et al*. 1997, 2001), bounded to the NE and SW by older highly deformed Archaean granodiorite gneisses.

Within the Kerrysdale amphibolite, two sulphide horizons have been identified, one pyritic, extending along strike for about 6km; and the other copper bearing, containing pyrite, pyrrhotite, chalcopyrite, sphalerite and native gold, extending along strike for about 1km (Jones *et al*, 1987). The style of mineralization is considered to be exhalative, and together with the presence of quartzite bands (metacherts ?) and striped magnetite quartzites (banded iron formation) strongly suggests a volcanogenic exhalative system, with similarities to well-known greenstone belt type mineralization.

From 1977 and 1983 Gairloch was explored by Consolidated Gold Fields Limited (latterly together with Outokumpu), who drilled 87 holes totalling 10,130m (Jones *et al*, 1987). A 'drill indicated and inferred' mineral resource has subsequently been estimated to contain 1.5Mt at an average grade of 1.8% copper, 0.6% zinc and 1.1 g/t gold. The mineralization, which has been modelled by Glasmin, is steeply dipping to the north at 75 to 80 deg. Structurally the mineralization appears to be confined to a block within two thrust planes, the Main Upper Thrust and the lower Western Basal Thrust, both pitching to the SE, and has been identified down to a depth of 400m below surface.

Between 1993-97, under the UK Government DTI-funded Mineral Reconnaissance Programme, the BGS carried out exploration in the Flowerdale Forest, located along strike and some 8km to the SE of the Gairloch Deposit. The BGS reported that "the succession at Loch Gorme na Beinne is similar to that at Gairloch and the presence of sulphide bearing banded iron formations (quartz magnetite schists) with significant gold values (up to 4 g/t) is highly prospective". Much of this area is obscured by overlying Torridonian Sandstones, with inlier 'windows' into the underlying Loch Maree Group.

Geochemical anomalies, related to the unusually high levels of Ni, Cu, Zn, V and Mg associated with the Loch Maree Group, are reported to extend further SE beneath the Moine nappe, as relatively high levels of first row transition elements are recorded in a zone extending SE along the Loch Maree fault, in both Moine metasediments and also the Lewisian area of Scardroy (Johnstone *et al*., 1979).

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Crustal anatexis during granulite facies metamorphism in the central region of the Lewisian Complex

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The Lewisian gneiss complex in NW Scotland is dominated by tonalite-trondhjemite-granodiorite (TTG) orthogneisses of Mesoarchaean age. Within these gneisses, mafic to ultramafic bodies, and spatially associated brown schists occur. On a large scale, the mainland Lewisian can be subdivided into northern and southern regions, which record amphibolite facies metamorphic conditions and a central region, which preserves granulite facies assemblages in many localities. The granulite facies metamorphic event (locally termed the Badcallian) is generally dated at around 2.8–2.7 Ga and records peak metamorphic conditions of 8.5–11.5 kbar and more than 900 °C. We provide field and petrographic evidence for partial melting of all major lithologies in the central region during the Badcallian event.

The most clear-cut evidence is preserved in migmatized metagabbros of the large layered mafic–ultramafic bodies (Johnson et al. 2012). Light-coloured patches and veins of coarse-grained plagioclase-rich leucosome are in strong contrast to the dark mafic host. These leucosomes contain euhedral peritectic clinopyroxene suggesting fluid-absent melting by reactions consuming plagioclase, hornblende and quartz. Segregation and migration of significant amounts of melt to higher crustal levels is indicated by connection of the leucosomes with laterally continuous tonalite or trondhjemite sheets.

Due to the limited colour contrast between quartzofeldspathic leucosomes and felsic hosts, evidence for partial melting of the volumetrically dominant TTG gneisses is much subtler. However, leucosomes containing peritectic ortho- and clinopyroxene indicative of melting reactions consuming biotite and hornblende can be identified more easily where they cross-cut the gneissose foliation (Johnson et al., 2013). In residual TTGs, partial melting is supported by rare microstructures showing intragranular cuspate films of K-feldspar, quartz and plagioclase representing former melt that was not extracted from grain boundary pores. Reactions consuming biotite led to the formation of leucosomes with peritectic garnet in the brown schists.

Based on the peritectic phases preserved in leucosomes, melting most likely occurred during the granulite facies Badcallian metamorphism, consistent with the high-grade conditions during this episode. Absolute dating of the melting event, and hence the peak of Badcallian metamorphism, using the U-Pb ages of zircons occurring in leucosomes is part of ongoing work. Despite over 100 years of research in the Lewisian, there are many open questions to be answered and the area remains a valuable field laboratory where future studies will aid in deepening our understanding of intra-crustal processes on the Archaean Earth.

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Noble metal enrichment in the margin of the North Atlantic Craton: Impacts for Ni-Cu-PGE mineralisation in W Scotland

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The role of the lithospheric mantle as a metal source for certain types of mineralisation, particularly orthomagmatic Ni-Cu-PGE sulphide deposits, is contentious [1,2]. Its role in metal sourcing may be physical and/or chemical, and the age and stability of the lithosphere may be critical. Mantle xenoliths reveal the mineralogy and bulk geochemistry of the lithospheric mantle. We use 6 suites of peridotitic mantle xenoliths obtained from a north-south transect of W Scotland, UK, to ascertain the major, trace element, and noble metal geochemistry of the lithospheric mantle keel below Scotland. This area straddles the margin of part of the North Atlantic Craton (NAC) including the marginal cratonic lithospheric keel and non-cratonic lithosphere.

Powdered whole-rock xenolith samples were subjected to ICP-OES and ICP-MS analysis for major and trace elements, and NiS fire assay with ICP-MS to determine PGE and Au abundances. The whole-rock data is evaluated in relation to the observed mineralogy and mineral chemistry of the xenoliths, as analysed by SEM and LA-ICPMS. This allows a rounded interpretation of the geologic history and major “enrichment” events that this portion of the NAC margin, and its surrounding terranes, experienced.

Most Scottish mantle xenoliths are spinel lherzolites, with rare wehrlites and dunites. Garnet-bearing peridotite xenoliths are entirely absent in this region. Where possible, xenolith suites were selected to be “fresh” with well-preserved pristine silicate mineralogy. Samples from within the Archaean craton at Loch Roag are haloed by a 3-5mm wide green-orange coloured alteration zone bearing Fe-oxide veinlets and vugs of baryte. In other xenolith suites, millimetre-scale flame-like veins of clinopyroxene, Cr-spinel and plagioclase have been preserved, representing frozen-in gabbroic partial melts (e.g., Hillhouse). Additionally, sub-millimetre anastomosing veinlets of chlorite ± ulvöspinel ± Ca-carbonate suggest interaction of a volatile-rich metasomatic agent (e.g., Streap). Abundant rounded sulphides (up to 150 µm diameter) occur interstitial to the main silicate mineral phases in all xenolith suites. These comprise intergrowths of Ni-Fe-Cu sulphides. Chalcopyrite can be absent from the sulphide assemblage. At Loch Roag, rare Pt-sulphide and Pt-arsenide grains up to 3 µm in length occur at a Cu-Fe sulphide margin.

Whole-rock trace element analyses demonstrate enrichment in LILE and LREE (10 – 100 x primitive mantle, PM) with corresponding depletion of Nb, Ta, Ti and Zr, Hf, indicating the geochemical influence of one/multiple subduction-like event(s). Overall the enrichment/depletion patterns are variable across W Scotland, but consistent within each xenolith suite, hinting at terrane-scale zoning across the Archaean craton margin into the neighbouring Proterozoic and Phanerozoic terranes to the south. Cu, Pt, Pd and Au concentrations are highly variable but always enriched above PM levels, and exceed concentrations in Greenlandic NAC and Kaapvaal cratonic peridotite xenoliths [4,5]. PGE+Au PM-normalised spidergrams display flat “fertile” patterns, suggesting little or no Pd-group PGE depletion took place prior to xenolith entrainment.

The trace element geochemical fingerprint of “subduction” and “metasomatism” is observed in all samples included in this study, and appears to be integrally linked to the Cu, Au and noble metal fertility of this lithospheric mantle region.

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Diamond Exploration in West Greenland – The Qaamasoq Prospect

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The Qaamasoq diamond prospect is situated within the Archaean West Greenland North Atlantic Craton (WG-NAC), approximately 130 km NE of the Greenlandic Capital, Nuuk. Whilst all know occurrences of kimberlitic rocks in Greenland are dykes or sills, with occasional blows up to approximately 4 meters in width (Jensen *et al*., 2004), examples of economic dykes of similar widths are known, for example the Snap Lake diamond mine in Canada (in production since 2008). However due to Qaamasoq's position high in the weathering profile of the WG-NAC, the potential for kimberlite pipes being preserved is greater in comparison to the more deeply eroded lower crustal levels of the craton. Previous exploration within the Qaamasoq licence area by Platinova / Cominco recovered a 0.28 x 0.28 x 0.21 mm clear, white macle diamond from a 34.6 kg kimberlite float sample (Aber Resources Ltd,1997). NunaMinerals A/S began exploration within the licence in 2010, flying a 2131 line-km helicopter-borne magnetic survey. Ground truthing of the resultant magnetic targets demonstrated that kimberlite float occurs abundantly at four localities, namely The Promontory, The Island, TMR-Q1-14 and Ullu. The abundance and size of mantle-derived kelyphitised pyrope garnet and the presence of eclogitic garnet within the kimberlites justified further evaluation. In addition the presence of large (>10cm) peridotite mantle xenoliths also demonstrated a carrying capacity for large diamonds, should they have been present within the source region. Hence bulk samples were collected for Diamond Indicator Mineral (DIM) separation and characterisation, and subsequently caustic fusion microdiamond analysis (in partnership with Rio Tinto Exploration and Mining Ltd). DIM analysis revealed that the majority fall within well-established prospective fields, particularly the mineral chemistry of the peridotitic- and eclogitic-garnet suites; some falling in the G10 (D) and G3 (D) fields (Grutter *et al*., 2004). The 'D' suffix is applied to garnet-categories with strong compositional and P-T association with diamonds (Grutter *et al*., 2004). The DIM chemistry is similar to the Garnet Lake diamond deposit, 150 km to the North, where the largest diamond from Greenland to date (2.4 ct) was recovered during reconnaissance sampling (Hutchison and Fri, 2009). Of the three samples processed from Qaamasoq, totaling 150.4 kg, all were found to be diamondiferous, resulting in six diamonds with the largest stone recovered from the 212-micron sieve. The processing of small samples such as these encompasses significant statistical uncertainties with respect to grade estimation. Hence the positive result is deemed encouraging and worthy of continued exploration. Ullu (Greenlandic for 'the Nest') is a NE-SW striking topographical depression situated only 1 km from a major terrane boundary between Archaean grey gneisses to the west and the Archaean Tasersuaq granodioritic gneisses to the east, within the vicinity of a regional noritic dyke. This significant tectonic boundary may represent an important control on kimberlite emplacement. Significantly Ullu also represents the northeast continuation of a highly prospective kimberlite indicator mineral trail previously identified by the Geological Survey of Denmark and Greenland (Jensen *et al*., 2004). The trend of the Ullu float extends 1 km to the distinct magnetic anomaly TMR-Q1-14. At Ullu over 200 boulders of kimberlite, up to 1.5 m in size occur within a well-defined 250 x 550 m area, partially covered by a glacial boulder field. Rare examples occur in which the kimberlite float at Ullu delicately preserves their contact with K-feldspar-phyric orthogneiss, which taken in combination with the volume of float observed supports a proximal, if not underlying source. Prior diamond exploration within the WG-NAC has shown that due to preferential weathering, it is unusual to be able to establish an in-situ source for kimberlite float without drill testing. It is expected that geophysical techniques such as ground magnetics or resistivity however, may assist in establishing the depth and dimensions of any buried source rock.

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Aillikite – an unconventional diamond host rock and its importance in the 'Greenland-- - Labrador-- - (Scotland?) Diamond province'

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Aillikite is the carbonate-rich endmember of the ultramafic lamprophyre (UML) clan (essential primary groundmass carbonate), macroscopically resembling kimberlite. It is commonly observed associated with, and grading into carbonatite. These typically highly volatile-rich (dominantly CO_2) ultrapotassic, strongly silica undersaturated, inequigranular, ultrabasic rocks (M> 90% - where M is defined as mafic and related minerals, i.e. including primary carbonate and apatite) are characterised by widely varying modal proportions of olivine and phlogopite macrocrysts and/or phenocrysts, and groundmass primary carbonate (calcite and/or dolomite), phlogopite (Al-Ti phlogopite which evolves by Al-depletion to Ti-poor tetraferriphlogopite), spinel (forming the 'tianomagnetite' trend and have Cr# <0.85), ilmenite, rutile, perovskite, Ti-rich garnets (melanite or schorlomite and kimzeyite) and apatite. Less commonly groundmass clinopyroxene (if present shows Al and Ti enrichment) and amphibole occur, at the expense of carbonate, more abundantly so within mela-aillikites. The prefix 'mela-' is applied to aillikites, which are more melanocratic (colour index >90%) due to the presence of the silicates, clinopyroxene and amphibole. In rare instances, monticellite may occur. Melilite, or the products of its subsolidus alteration, leucite and nepheline, are absent, else the UML would classify as either an alnöite (essential groundmass melilite) and damtjernite (essential groundmass nepheline and/or alkali feldspar). Alteration, sometimes extreme, typifies the vast majority of aillikites, resulting from the deuteric reaction between early crystallising phases and residual carbonate-rich fluids (autometasomatic alteration). Many aillikites in West Greenland (WG) show several mineralogical characteristics corroborating with a kimberlite affinity, but with one or more of the critical criteria not complying with the strict definition of kimberlite *s.s.* In WG at least, the diamond prospectivity of the intrusions does not appear to be dependant upon them being kimberlite *s.s* or aillikite, with some aillikites hosting sub-economic grades of diamond despite them not being considered conventional host rocks. Recently several exploration companies have taken up licences over areas of aillikitic magmatism for diamond exploration in the 'Greenland---Labrador Diamond Province' (GLDP), with the most advanced exploration at Garnet Lake, near Safartôq in WG. The recent discovery of the first reported occurrence of aillikite from the UK, in northwest Scotland opens up the potential for the 'Greenland-Labrador-Scotland Diamond Province' [1]. The growing number of aillikite occurrences shown to be diamond-bearing demonstrates that aillikite magmatism has the potential to sample diamondiferous parts of the sub-continental lithospheric mantle. Hence, the potential exists for lamprophyres (particularly var. aillikite) to be the next group to move into the conventional category as a primary source of diamond, and thus represent a worthy exploration target. It is cautiously postulated that with respect to diamond exploration the exact petrographic classification may be extraneous, as long as the carrier melt can be proven to have originated from well within or below the diamond stability field and rapidly emplaced at the surface or near surface at a rate that minimises reabsorption and allows the survival of entrained diamond. Indeed it is evident that there is a substantial lack of research into determining how wide the field of diamondiferous rocks extends, and how this affects traditional diamond exploration methods, such as diamond indicator mineral chemistry. It is negligent to assume that a mantle-derived igneous rock displaying evidence of an origin within the diamond stability field should be excluded from exploration just because it is not kimberlite *s.s*

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The Geological Survey of Denmark and Greenland (GEUS) opened a new branch in Nuuk in Greenland. The new office had official opening on September 26, 2013, and is located at the Greenland Institute for Natural Resources, in a scientific environment and next to the University of Greenland.

There are permanently two employees, but other GEUS employees will be passing through in limited periods. The office has a strong scientific background with more than 340 employees at GEUS in Denmark.

The aim of the office is to bring the geological knowledge closer to Greenland, as a gateway to geology in Greenland, which delivers facts, information and data. The office intends to assist individuals, companies, politicians, authorities and institutions in Greenland, and to maintain and improve the collaboration with the Greenlandic administration, industry and academic collaboration partners. Another important task will involve further outreach, teaching and availability to higher educational institutions, schools, tourists and other.

How hot was the British Tertiary mantle plume? New constraints from high-Mg picrites on Skye and Rum

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A suite of picrite dykes from the British Tertiary Igneous Province of north west Scotland were collected from the Skye and Rum central volcanic complexes. The picrites represent primitive, high-MgO ultrabasic melts and are rich in olivine phenocrysts. Small crystals of chrome spinel and at least two generations of olivine are present. The first group are highly forsteritic, ranging up to almost Fo93. The second group are less magnesian, ranging up to Fo90. Highly forsteritic olivines are proposed to have crystallized at depth from a high-Mg liquid in equilibrium with mantle olivines, similar to Palaeogene picrites observed in West Greenland (Larsen and Pedersen, 2000).

Using PRIMELT2 (Herzberg and Asimow, 2008), parental liquids are estimated to have contained 16-20 wt% MgO, corresponding to a mantle T_P of 1490-1570ºC, representing a thermal anomaly 200-250ºC above ambient conditions. The results suggest that large thermal anomalies were present across a widespread area affected by the early Iceland mantle plume.

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The Lost Gardar Intrusion: Critical Metal Exploration at the Paatusoq Syenite Complex, South East Greenland

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Regional mapping by GEUS (Garde, 1998) of the Paatusoq region, South-East Greenland, defined two intrusive centres, the Paatusoq Gabbro (~23km^2) and the Paatusoq Syenite (~240km^2). These intruded the lithospherically weak boundary between Ketilidian meta-sedimentary rock to the East and to the West the Pelite-Psammite zone sediments unconformably overlying the Julianehåb batholith. Following the discovery of high rare earth element (REE=La-Yb+Y) anomalies in stream sediments (Steenfeldt, 2012) in the Paatusoq region, Paatusoq was the target of exploration by Nuna Minerals A/S in June 2013. The objective was to provide an assessment of the critical metal potential of the region. Exploration involved helicopter reconnaissance and sampling.

The Paatusoq syenite (1144±1 Ma) was recognised by Garde (2002) as part of the Gardar Alkaline Igneous Province (1300-1140 Ma). Gardar centres are predominantly found on the South-Western coast and represent products of magmatism associated with repeated Mesoproterozoic rifting. Globally significant critical metal deposits are associated with the province including Motzfeldt (Ta-Nb) and Ilímaussaq (REE-Zr-Nb). Gardar intrusions with significant critical metal mineralisation often record interaction with late-stage fluorine-bearing fluids. Analysis integrated petrography and geochemistry, supplemented by two indicators of fluid interaction with the syenite; the cathodoluminescence textures of feldspars and the halogen content of biotite.

The Paatusoq Gabbro showed heterogeneous primary layering and pegmatite schlieren to the West against the syenite. A Gardar Lamprophyre dyke cuts the Gabbro. Petrology showed; subhedral olivine, labradorite, biotite and quartz. Incompatible element geochemistry showed the gabbro has a Zr/Nb ratio >15 consistent with a Ketilidian affinity and the lamprophyre has a Zr/Nb ratio ~5, comparable with other Gardar lamprophyres.

The Paatusoq syenite showed lithological variation from quartz-augite-syenite to syenodiorite. Steep contacts and xenolith zones indicate stoping was the mechanism of intrusion. The last expressions of magmatism were alkali granite sheets, often subsequently bisected by dolerite. Petrology showed cryptoperthitic feldspars with quartz, aegirine-augite, biotite and ilmenite-pyrophanite. The syenite has a Zr/Nb ratio <10 consistent with a Gardar signature.

Cathodoluminescence shows the alkali feldspars display bright blue-green Fe^{2+} luminescence in contrast to the red Fe^{3+} luminescence observed in many other Gardar intrusions which have experienced fluid interaction. Orange luminescent carbonate micro-veins and striking green luminescent apatite and zircon with concentric zonation textures are preserved in the roof zone of the intrusion. Analysis of the halogen content of the biotites in syenite and lamprophyre samples demonstrated Fe/(Fe+Mg) ratios between 0.3-1 and Fwt% values with a variation of 0-2.5. An inferred Maximum Fluorine Line (Finch, 1995) defines a trend comparable to the evolved Motzfeldt centre, which is among the most F-rich fluid environments in the Province.

This exploratory assessment develops our understanding of the easternmost extent of Gardar magmatism. The high fluorine content of biotite and apatite, zircon and carbonate mineralisation, indicate the syenite, particularly the roof zone, experienced interaction with fluorine and carbon dioxide-bearing late stage fluids. Apatite zoning shows REEs were mobile in this fluid. Preliminary observations indicate that Paatusoq is an unusual Gardar centre commensurate to the main Motzfeldt centre making it an area of consideration for future REE exploration.

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Ellesmerian-aged reactivation of soft-sediment deformation structures in the evaporite-rich Cape Webster formation of the Franklinian Basin, Washington Land, North Greenland.

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The Franklinian Basin is a Neoproterozoic to late Devonian depocentre that evolved at low palaeolatitudes on the margin of the Laurentian supercontinent. The sedimentary succession is volcanic-poor and consists of shelf, shelf slope and trough, carbonate and clastic sediments. The deepest part of the basin is to modern-day north and this gradually migrated towards modern-day south as sedimentary loading and tectonic events swamped the shelf, culminating in basin closure during the Ellesmerian Orogeny. Conventionally, Ellesmerian orogenic structures, which are predominantly shortening related, are not found south of the Ordovician shelf edge, the Navarana Fjord Escarpment. In North Greenland, in Washington Land, Cambrian to Ordovician shelf sediments contain evaporite deposits. In the Ordovician Cape Webster Formation of the Ryder Gletchser Group soft-sediment and brittle–ductile structures appear to be associated with evaporitic units. A low angle detachment structure with development of thrusts, and fault propagation folding, is developed parallel to bedding surfaces that show soft sediment deformation with fluid escape structures. The mud-rich Cape Webster Formation in the vicinity shows breccias and complex fault structures that may be related to loss of evaporites. Tectonic transport direction indicated by thrust and fold polarity, and fault lineations, is to modern-day south, consistent with Ellesmerian Orogeny tectonic transport directions. The nearest Ellesmerian deformation structures are developed more than 60 km to the north. Two potential models are examined: a hybrid model where early soft sediment deformation structures, related to evaporites, created a zone of weakness that is later reactivated by low-angle thrusting as a distal expression of Ellesmerian shortening to modern-day north; and a model where evaporite-related soft sediment deformation structures are reactivated by loading-related gravity sliding during basin evolution. Confirmation of the first model would be the first identification of Ellesmerian-orogeny-style contractional structures in Washington Land and would represent the southernmost expression of shortening associated with the orogeny.

The Kangerluarsuk SEDEX Lead-Zinc Project, West Greenland.

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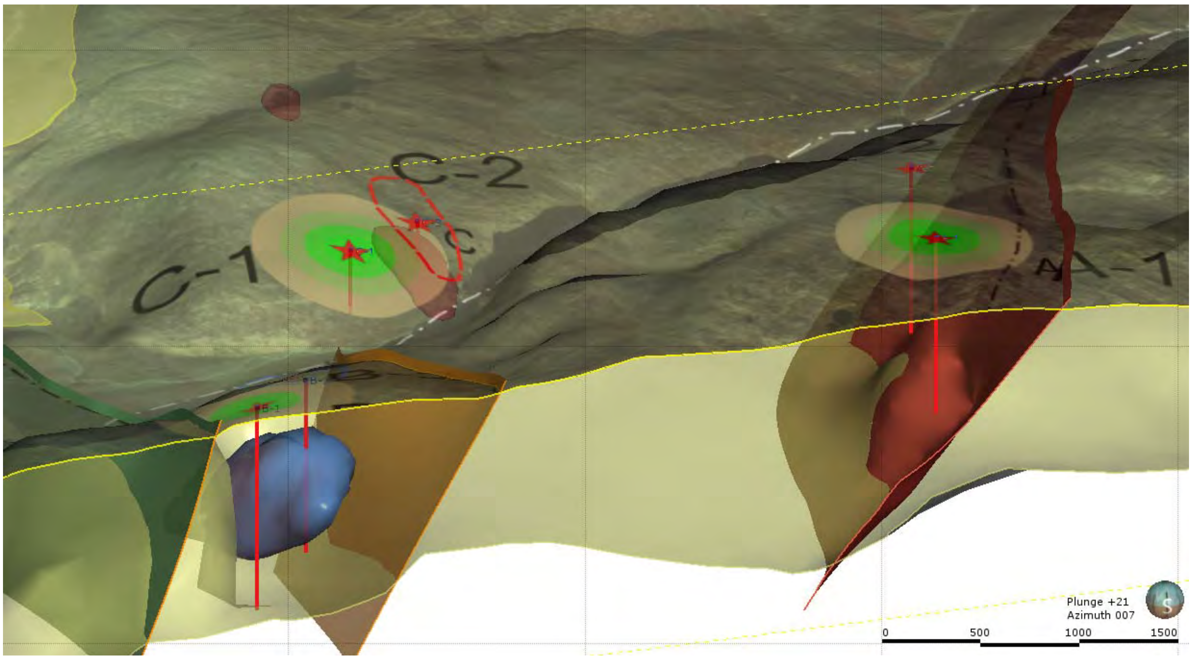
The Kangerluarsuk Zinc Project consists of exploration activities within a 126 km2 licence situated in an area with proven zinc potential close to the historically very profitable Black Angel Mine (11 million tons of ore averaging 12% Zn, 4% Pb and 29 ppm Ag).
The geological setting, at the margin of a starved Palaeoproterozoic basin adjacent to a MVT mineralised carbonate platform is analogous to the McArthur basin in Australia that host a series of large SEDEX deposits. The potential was first recognized in 1992 after RTZ demonstrated the presence of thin, but high-grade SEDEX-style mineralizations at the basin margin. Subsequently, the Geological Survey's regional stream sediment sampling program identified the Kangerluarsuk area as having the most prominent and persistent zinc anomalies in the entire sedimentary basin. The zinc anomalies correlate with marked positive copper and nickel anomalies, which may indicate a polymetallic SEDEX deposit with Rammelsberg in Germany as a close analogue.

During 2011-2013 Avannaa has conducted geological mapping, structural analysis and geochemical and geophysical surveys to target a buried SEDEX deposit and to locate drill sites including:

- 975 soil samples that were tested for Mobile Metal Ion (MMI), Soil Gas Hydrocarbon (SGH) and bulk chemistry. **Three deep targets** were identified, one achieving the **highest possible ranking (6.0)** within the SGH system.
- A deep penetrating magnetotelluric survey (ZTEM) was conducted in 2012 and detailed 3D inversion indicates the existence of **two conductors** at 6-700 m's depth, which correlate with the soil sample anomalies.
- The basin has been mapped in detail at 1:10,000 scale and structural analysis suggest presence of **growth faults** spatially associated with soil sample anomalies and the two conductive bodies.



3D model of the central Kangerluarsuk geology showing the Two Lakes fault and other faults extrapolated to depth. Top basement inferred using resistivity and magnetic data has resolved basement steps across all the faults. The Two Lake fault has an extension separation at the top basement that is much greater than at outcrop implying total slip at depth of at least 600m indicating this as a syn-sedimentary growth fault. Projected drill holes shown in red star and line, geochemical anomalies A, B & C in buff-green circles and appertaining 0.01 S/m conductivity iso-surfaces in dim blue and terracotta.

Motzfeldt: A multi-element package opportunity in the Gardar Province, South Greenland

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Greenland Resources is a UK-registered company that holds 100% interest in two exploration licences at Motzfeldt, South Greenland. The Company is 51% owned by Ram Resources Limited (ASX:RMR) and 49% by Quayside Services Limited (Quayside). The commodities sought are 'speciality metals,' a multi-element element package of Nb-Ta-Zr-Th-U and REE minerals. These are becoming increasingly important for the production of greener technologies required by todays' cleaner energy sensitive markets. Until recently, the main contributor of the world's quota of REE (~97%) was China but, in order to supply their own increasing demand they have imposed strict limitations on their export quotas. In response, other countries are now having to locate alternative sources for these critical metals. Alkaline complexes of the Baltic Shield and Greenland are seen as viable contributors to this burgeoning market and, strategically situated midway between North America and Europe, the southern tip of Greenland is opening itself up to its mining possibilities.

The 1.2Ga Motzfeldt Centre, is one of the major centres in the Proterozoic Gardar Alkaline Province, a region that also hosts the renowned ilimmaasaq intrusion. Comprising peralkaline syenites, nepheline syenites, syenites, pegmatites and lujavrites, this geological environment has undergone extreme *in-situ* fractionation resulting in late-stage incompatible element enrichment. Previous exploration at Motzfeldt had focussed essentially on Nb-Ta-U mineralisation in pyrochlore and in 2012 the Company announced a **Total Inferred Mineral Resource of 340 million tonnes at 120ppm Ta_2O_5,1,850ppm Nb_2O_5, 4,600ppm ZrO_2 and 2,600ppm TREO** at its Aries prospect (Pittuck, 2012). Pyrochlore tends to be preferentially LREE enriched and supplies of the LREE (with the possible exception of Nd) are relatively secure in line with demand but the HREE is considered to be at risk. The occurrences of zircon and eudialyte at Motzfeldt are important repositories for the HREE and the project offers resources and an exploration footprint that forms the perfect platform for Mining companies expanding their interest into Greenland.

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The Melville Bugt Dyke Swarm, Greenland: Precise U-Pb ages, Geochemistry, Paleomagnetism and Possible Late Paleoproterozoic Connections with Baltica or Amazonia

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Results are presented from an integrated U-Pb geochronological, geochemical and paleomagnetic study of the Melville Bugt dyke swarm from Greenland. The swarm comprises mostly trachybasalt dykes up to 200 m in width (average ~80 m) intruding Rinkian gneisses and metasediments of Archean and Paleoproterozoic age, and were thought to extend for at least 1200 km in a NNW-SSE direction, from north of Thule in the north (~78°N) towards Ilulissat in the south (69°N) before disappearing under Greenland's inland ice cap. Several of these dykes yielded precise U-Pb (baddeleyite) ages ranging from 1635 to 1622 Ma. Satellite imagery from remote South-East Greenland shows several NNW-trending dykes, which allowed us to speculate on a long-range southerly continuation of the Melville Bugt swarm under the inland ice (Halls et al., 2011). Subsequent field mapping support from the Danish and Greenland Geological Survey along the exposed southeast coast has permitted investigation of these dykes, and initial U-Pb dating studies by one of us (MKMN) confirm the presence of Melville Bugt dykes in this age range, almost doubling the known length (and volume) of the swarm. Field and mineralogical characteristics of these dykes are strikingly similar to those exposed in North-West Greenland, and continuation of the Melville Bugt diabase dyke swarm across the widest transect of the North Atlantic craton appears indisputable. This now ranks globally among only a few other of the great mafic magmatic events such as those which produced the Franklin, Mackenzie and Matachewan swarms of Canada in terms of strike length.

The sense of a magnetic polarity change in the Melville Bugt dykes has been obtained in coordination with the precise geochronology, in which a SW-directed down magnetization is older (1635 ± 3 to 1632 ± 1 Ma) than an upward, NE-directed remanence (1629 ± 1 to 1622 ± 3 Ma). Assuming only one polarity change during this interval, the same field reversal may be recorded by the 1633 Ma Sipoo dykes of Finland, where approximately antipodal remanences of similar direction have the same relative age from magnetic overprinting studies. This observation raises the possibility that the 1.63 Ga Melville Bugt dyke swarm once trended towards the 1.5–1.6 Ga rapakivi province in Baltica, or a possible extension in Amazonia, raising the conjecture that the dyke swarm was fed laterally from one of these magmatic provinces. The use of high precision U-Pb geochronology to establish the sense of paleomagnetic reversals promises to be a useful tool in continental reconstructions.

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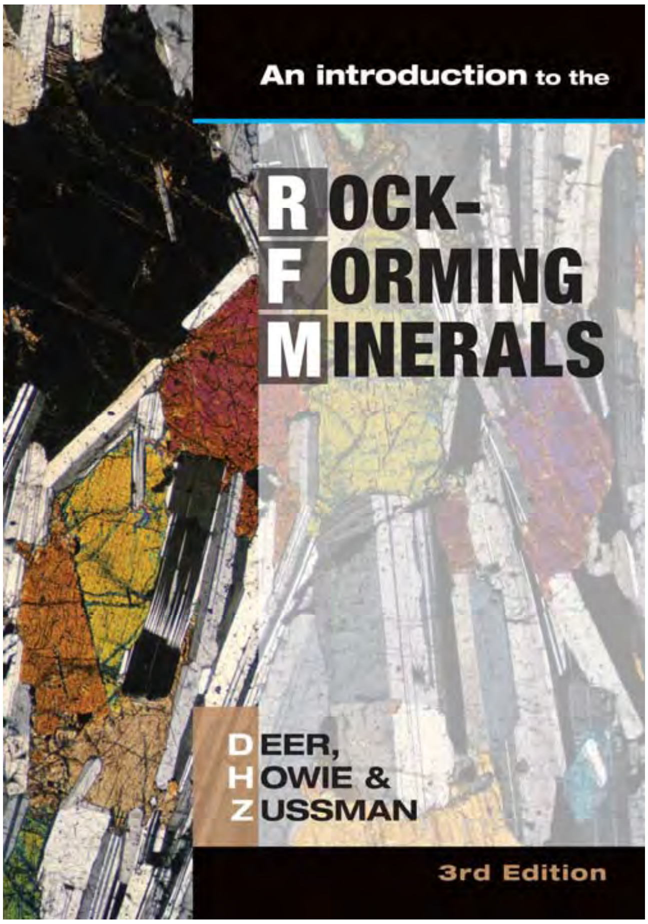

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