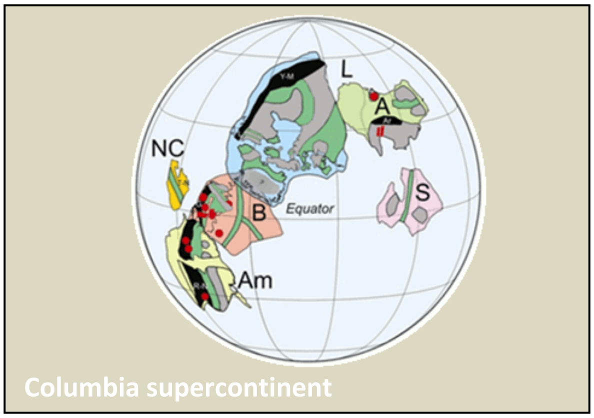

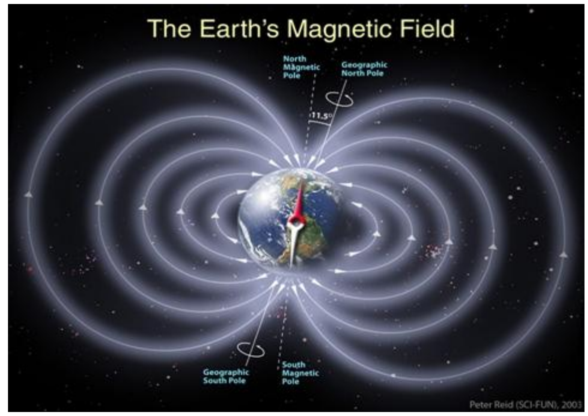

September 25-28, 2012. University of Helsinki, Finland

SUPERCONTINENT SYMPOSIUM 2012

Programme and Abstracts

Satu Mertanen, Lauri. J. Pesonen and Pathamawan Sangchan

GTK

UNIVERSITY OF HELSINKI

Supercontinent Symposium 2012

September 25-28, 2012
University of Helsinki, Finland

Programme and Abstracts

Edited by Satu Mertanen, Lauri J. Pesonen and Pathamawan Sangchan

Geological Survey of Finland, Espoo, Finland

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Preface

This Abstract Volume contains seventy four abstracts submitted to the Supercontinent 2012 Symposium to be held during Sept. 25-28, 2012 at the Kumpula Campus of the University of Helsinki, Finland (http://supercontinent2012.helsinki.fi/). The four days symposium focuses on current knowledge and problems regarding supercontinent research with a focus on the Precambrian era. Some seventy geoscientists from around the world will arrive in Helsinki to discuss the recent developments and problems in the research of supercontinents, their assemblies and break-ups and to raise new ideas. The Symposium will be preceded by an Excursion through seven geological landmark sites in Finland. Twenty seven scientists will participate in the excursion.

This Volume is edited by Satu Mertanen, Lauri J. Pesonen, Pathamawan Sangchan and Ella Koljonen. We thank Kari Jääskeläinen, Tuire Laine, Robert Klein, Tommi Vuorinen, Johanna Salminen and Toni Veikkolainen for their help in preparing this Volume and the Symposium. The publishing of the Abstract Volume was made possible with the help of the Geological Survey of Finland. The symposium would not be possible without the help of scholarships by the Finnish Cultural Foundation, the Finnish Academy of Science and Letters, the Finnish Society of Sciences and Letters and financial and logistic support by cities and towns of Helsinki, Keuruu, Lappajärvi, Rovaniemi and Tervola. We also thank Keijo Hämäläinen, Kaarlo Hämeri, Tuulikki Pitkänen, Anu Palo and Pirjo Käyhkö for their help in organising the Symposium.

Welcome to the Supercontinent Symposium 2012 in Helsinki, the “Daughter of the Baltic Sea” and the host of the World Design Capital 2012!

Kumpula, Sept. 17, 2012

Lauri J. Pesonen
Solid Earth Geophysics Laboratory
University of Helsinki

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KAUPUNGINJOHTAJA, YLIPORMESTARI JUSSI PAJUSEN TERVEHDYS

SUPERMANNER SYMPOSIUMIN OSALLISTUJILLE 25.9.2012

Arvoisat Supermanner Symposiumin osallistujat

Toivotan teidät lämpimästi tervetulleiksi Helsinkiin ja Suomeen. Tulette tekemään mielenkiintoisen aikamatkan Supermanner Symposiumin kuluessa. Historian tutkiminen ja tunteminen lisää nykypäivän ymmärrystä sekä auttaa hahmottamaan tulevaisuuden suuntaviivoja.

Symposium on perusteellisen valmistelun ja monen eri tahon hyvän yhteistyön tulosta. Kokoontuminen yhteen alan parhaan asiantuntemuksen ja uusimmat tutkimustulokset.

Isäntäkaupunkina haluamme tarjota parhaat mahdolliset puitteet kokoukselle. Helsingin keskeisiä vetovoimatekijöitä ovat toimivuus ja turvallisuus. Päätöksenne kokoontua Helsingissä juuri tänä vuonna on mitä otollisin, sillä kaupungissa tapahtuu tällä hetkellä poikkeuksellisen paljon.

Käynnissä on monessa eri mielessä juhlavuosi. Huhtikuun 8. päivänä tuli kuluneeksi tasan 200 vuotta Helsingin korottamisesta Suomen pääkaupungiksi. Tämän lisäksi Helsingillä on kunnia toimia maailman designpääkaupunkina yhdessä metropolialueen muiden kuntien kanssa. Lähestymme muotoilua laaja-alaisesti ja tavoitteemme on edistää sillä taloudellista, sosiaalista ja kestävää kehitystä.

Supermanner Symposium levittäytyy laajalle maantieteelliselle alueelle Suomessa. Maan monipuoliset maisemat ja maastot kertovat niistä voimista, jotka ovat muovanneet elinympäristömme aikojen saatossa nykyiselleen. Tälläkin hetkellä Helsinki elää historiallisessa murrosvaiheessa. Se on seurausta entisten satama-alueiden ottamisesta asuinkäyttöön. Kaupungin olemus muuttuu merkittävästi ja merelliset juuremme korostuvat.

Toivonkin kovasti, että mielenkiintoisen kokousohjelman lisäksi ehditte tutustumaan itse kaupunkiin. Tarjolla on muun muassa lukuisia designaiheisia näyttelyjä ja tapahtumia. Lisäksi merellinen Helsinki kannattaa ehdottomasti kokea.

Toivotan mitä antoisimpia tutkimuspäiviä kaikille symposiumin osallistujille!

Jussi Pajunen

kaupunginjohtaja

		SUPERCONTINENT SYMPOSIUM 2012
		DAILY PROGRAMME (Physicum, lecture hall D101)
Tuesday , Sep. 25		
19:30	Ice breaker in "Pub Rodinia", Park Hotel Käpylä	
Wednesday , Sep. 26		
9:00-9:15	**Juha Karhu and L.J.Pesonen: opening remarks & practical things**	
Morning talks	Session A1: Supercontinents, LIPS, dyke swarms... Chair: Sten-Åke Elming	
9:15-9:40	Trond Torsvik (inv.)	Supercontinents, LIPS, kimberlites and the deep mantle
9:40-10:00	Andrey Bekker	Relationship among supercontinent assembly, superplume events, and secular trends in VMS and iron formations
10:00-10:20	Richard Ernst et al.	Constraints from the LIP barcode record and associated giant dyke swarms for supercontinent reconstructions: progress report on the LIPS-supercontinent project
10:20-10:50	*Coffee break at "Poster Hall"*	
	Session A2: Supercontinents, models... Chair: Henry Halls	
10:50-11:15	Ken Buchan (inv.)	Testing Precambrian supercontinent reconstructions with paleomagnetic 'key pole' data
11:15-11:35	Bruce Eglington et al.	Creating plate reconstruction models and animations for the Precambrian utilising information from the IGCP 509 databases and structural vergence directions to supplement palaeomagnetic information
11:35-11:55	Sally Pehrsson et al.	Animated assembly of supercontinent Nuna: global orogenesis and metallogeny
11:55-12:15	Svetlana Bogdanova et al.	1.80-1.75 Ga Mafic dykes in the Ukrainian shield - a key to the paleogeography of Baltica within Columbia
12:15-13:15	*Lunch in Chemicum*	
Afternoon talks	Session A3: Paleomagnetism and supercontinents I… Chair: Satu Mertanen	
13:15-13:40	Sergei Pisarevsky (inv.)	Mesoproterozoic supercontinent - paleomagnetic synthesis and geological constraints
13:40-14:00	Sten-Åke Elming et al.	Basic dykes from southern Sweden: paleomagnetic signatures, a 935-939 Ma key-pole for Fennoscandia and tectonic coherence with Southwestern Scandinavian province
14:00-14:20	Joseph Meert et al.	Indian Precambrian Paleomagnetism: Updates and future efforts
14:20-14:40	Elisa Piispa et al.	Cross-cutting Proterozoic dyke swarms of Dharwar craton, India
14:40-15:10	*Coffee break at "Poster Hall"*	
	Session A3 (cont.): Paleomagnetism and supercontinents II… Chair: David Evans	
15:10-15:35	Ricardo Trindade (inv.)	Recent advances in paleomagnetism of South America: relevance for Proterozoic supercontinents
15:35-15:55	Mike Hamilton et al.	The nature, origin and precise U-Pb geochronology of the 1.63 Ga Melville Bugt Swarm, Greenland: Testable links with the 1.5-1.6 Ga Baltic rapakivi province?
15:55-16:15	Johanna Salminen et al.	Paleomagnetic study of the Mesoproterozoic Satakunta dyke swarm, Finland, with implications for a Northern Europe – North America (NENA) connection within Nuna supercontinent

16:30-17:50	**Part I of poster session: short oral presentations (2 min. each) Chair: David Evans**	
	Altogether 29 posters	
	Emilia Koivisto et al.	Plate motions relative to the global hotspots for the past 48 million years
	Mathew Domeier et al.	The paleogeography of Pangea: progress and problems
	Mike Hamilton et al.	A precise U-Pb age for the Great Whin Dolerite Complex, N.E. England: dating the European Permo-Carboniferous LIP and rift event in the Pangean supercontinent
	Roman Veselovsky et al.	Paleomagnetism of Devonian dykes from the northern Kola Peninsula and its implications to the evolution of Precambrian Supercontinents
	Anna Nosova et al.	Kimberlites and lamproites of the northern east European craton: position in supercontinental cycles
	Robert Klein et al.	Paleomagnetizations in Central Finland: Keuruu dyke swarm and shatter cones from Keurusselkä meteorite impact structure
	Mikko Nironen et al.	Ultra-mature quartzites in Southern Finland: was Baltica part of supercontinent Columbia during 1.85 Ga?
	Alexandra Stepanova et al.	2.14 Ga Morb-type tholeiitic dykes on the Karelian craton:possible time-marker of the breakup
	Johanna Salminen et al.	Paleomagnetic and rock magnetic studies on the 2.45-2.1 Ga diabase dykes of Karelia, East Finland – key for testing the proposed Superia craton
	Svetoslav Sokolov et al.	Paleomagnetism of the Proterozoic ultramafic-mafic dykes of the Onega structure (preliminary results)
	Kaisa Nikkilä et al.	Lateral flow in middle crust– Experiments from Svecofennian belt
	Annakaisa Korja et al.	North European transect (NET) – growth of Northern Europe in supercontinent cycles
	Pasi Eilu et al.	Fennoscandian 2.7-1.7 Ga metallogeny and supercontinent cycles
	Victor Puchkov	The Odissey of Baltica
	Mauro Cesar Geraldes et al.	Mesoproterozoic westward growth in the SW Amazonian craton: recent advances on global correlations within a Middle-Proterozoic supercontinent
	Franklin Bispo-Santos et al.	Paleomagnetic study of the 1.98-1.96 Ga Surumu Group from northern Brazil: the Paleoproterozoic Amazonian craton APW path and paleogeographic implications.
	Franklin Bispo-Santos et al.	The 1.8-1.78 Ga Avanavero magmatism - paleomagnetic evidence for the SAMBA (South America and Baltica) reconstruction in Columbia supercontinent
	Elson Oliveira et al.	New U-Pb zircon-baddeleyite ages on Archaean to Neoproterozoic LIPS (mafic dykes) of the São Francisco Craton, Brazil, and their potential use for palaeocontinent reconstruction
	Ticiano José S. d. Santos et al.	The metamorphic age of the Forquilha eclogite belt in the NW Borborema province, NE Brazil
	Nasrrddine Youbi et al.	U-PB geochronology of dyke and sill swarms of the West African craton (Anti-Atlas inliers): possible links to break-up of Precambrian supercontinents
	Elisa Piispa et al.	Paleomagnetism of lamprophyre dykes near Marathon, Ontario, Canada - early stage of midcontinent rift volcanism?
	Robert Cundari et al.	Geochemistry and paleomagnetism of the Devon Township basalt, Ontario, Canada
	Lauri Pesonen et al.	New paleomagnetic data of the Wajrakul kimberlite swarm constraining the onset of Rodinia
	Lauri Pesonen et al.	Paleo-Mesoproterozoic supercontinents – a paleomagnetic view
	Chandrappa Shashikala et al.	Supercontinent studies - implication on gold metallogeny
	Ross Mitchell et al.	Supercontinent cycles and the calculation of absolute paleolongitude in deep time
	Lauri Pesonen et al.	A novel Precambrian paleomagnetic database: The basis for analysing supercontinents, GAD and PSV
	Toni Veikkolainen et al.	The reliability of the geocentric axial dipole model as evaluated from the reversal asymmetry of the Precambrian geomagnetic field
	Toni Veikkolainen et al.	Paleosecular variation in the Precambrian and the validity of the geocentric axial dipole theory
18:00 →	**Part 2: Poster session continues at Poster Hall**	
18:00 →	Buffet dinner at Poster Hall	

Thursday, Sep. 27		
Morning talks	Session B1: Paleogeomagnetism, magnetic field... Chair: Ken Buchan	
9:00-9:20	Phil Schmidt	Refining the Australian Neoproterozoic APWP – inclination corrections
9:20-9:40	Toni Veikkolainen et al.	The Precambrian geomagnetic field has no prominent low-inclination bias
9:40-10:00	Nicholas Swanson-Hysell et al.	Reinforcing the paleomagnetic backbone of Rodinia: new constraints on the late Mesoproterozoic Keweenawan track
10:00-10:20	Fabio Donadini et al.	Symmetric and asymmetric reversals in the 1.1 Ga Central Arizona diabases: the debate continues
10:20-10:50	*Coffee break at "Poster Hall"*	
	Session B2 : Paleogeomagnetism, reconstructions... Chair: Ricardo Trindade	
10:50-11:10	Suzanne McEnroe et al.	Magnetic mineralogy and paleomagnetism of Proterozoic Grenville metamorphic and igneous rocks of the Adirondack Highlands
11:10-11:30	Elisa Piispa et al.	The paleomagnetism, geochemistry and geochronology of the Mesoproterozoic midcontinent rift dyke swarms from Baraga - Marquette area, USA and Thunder Bay area, Canada - the onset of Rodinia
11:30-11:50	Robert Klein et al.	Paleomagnetic study of Satakunta sandstone, SW-Finland: implications for Baltica during the Proterozoic
11:50-12:10	Natalia Lubnina et al.	New palaeomagnetic and geochronological data from the Ropruchey sill (Karelia, Russia): implications for late Palaeoproterozoic palaeogeography
12:10-13:10	*Lunch in Chemicum*	
Afternoon talks	Session B3: Geological models, new reconstructions... Chair: Sally Pehrsson	
13:10-13:30	Åke Johansson	From Rodinia to Gondwana with the 'Samba' model – a distant view from Baltica towards Amazonia and beyond
13:30-13:50	Mike Hamilton et al.	Nain/Gardar-aged mafic dykes as a temporal and magmatic 'bridge' across North Atlantic cratonic blocks: geochronologic, paleomagnetic and geochemical evidence from Labrador and SW Greenland
13:50-14:10	Tatiana Donskaya et al.	Paleoproterozoic granitoids marking the Siberian craton and pre-Rodinia supercontinent assembly
14:10-14:40	Reinhardt Fuck et al.	5000 km of intercontinental shear zone: the Transbrasiliano-Kandi lineament in Brazil
14:40-15:00	*Coffee break at "Poster Hall"*	
	Session B4: Reconstructions, tectonics... Chair: Sergei Pisarevsky	
15:00-15:20	Henry Halls	Paleomagnetic evidence for crustal shortening during the Paleoproterozoic
15:20-15:40	Benjamim Bley de Brito Neves et al.	The basement of the South American platform: Half Laurentian (N-NW) + half Gondwanan (E-SE) domains
15:40-16:00	Guiting Hou	Mechanism of supercontinent Columbia fragmentation
16:00-16:20	Taylor Kilian et al.	The role of the Wyoming craton in Paleoproterozoic supercontinents or supercratons: New paleomagnetic and geochronologic data from multiple dyke swarms
16:20-16:30	10 min pause	
16:30-17:00	**Public lecture : L.J. Pesonen**	Continents and Supercontinents
17:00-18:00	**Poster session at Poster Hall**	
18:15-19:00	Transportation to downtown University campus by "Streetcar named Larambia"	
19:00-20:45	Rector's buffet dinner in "Press-Hall", Downtown campus, Main building	
21:10	Bus transportation to Park Hotel Käpylä	

Friday, Sep. 28		
Morning talks	Session C1: Datings, models... Chair: Hannu Huhma	
9:00-9:20	Alex Deutsch et al.	Precisely dated impact structures and their use in supercontinent research
9:20-9:40	Laura Lauri et al.	New age constraints for the Paleoproterozoic felsic volcanic rocks associated with the Koillismaa intrusion, Finland
9:40-10:00	Peter Sorjonen-Ward	A rudimentary event history for mineral systems in Finland – local phenomena or responses to global events?
10:00-10:20	Camila Nogueira et al.	The Santa Clara rapakivi massif: within-plate magmatism in the SW of the Amazonian craton during the final stages of Rodinia agglutination
10:20-10:50	*Coffee break at "Poster Hall"*	
	Session C2: Isotopes, geological events… Chair: Tom Andersen	
10:50-11:10	Juha Karhu	Termination of the Paleoproterozoic carbon isotope excursion: evidence from the northern Fennoscandian shield
11:10-11:30	Hannu Huhma et al.	Age and Sm-Nd isotopes of Palaeoproterozoic mafic rocks in Finland – rifting stages of Archaean lithosphere and multiple mantle sources
11:30-11:50	Wilson Teixeira et al.	Juvenile accretion (2360-2330 Ma) in the São Fransisco craton, and implications for the Columbia supercontinent: U/Pb ages, Sr-Nd-Hf and geochemical constraints from plutonic rocks of the Mineiro belt
11:50-12:10	Robert Cundari et al.	Petrogenesis and crustal contamination of the Nipigon sills: a geochemical and spatial re-evaluation
12:10-13:10	*Lunch in Chemicum*	
Afternoon talks	Session C3: Models, geochronolgy… chair: Bruce Eglington	
13:10-13:30	Tom Andersen	The detrital zircon record: Supercontinents, parallel evolution - or coincidence ?
13:30-13:50	Dmitry Gladkochub et al.	LA-ICP-MS U-PB Dating of detrital zircons from sediments of the southern part of the Siberian craton: constraints for Precambrian supercontinents
13:50-14:10	Zheng-Xiang Li et al.	Global Cryogenian and Ediacaran paleogeography: a new kinematic and lithostratigraphic model
14:10-14:30	Harald Walderhaug et al.	Baltica in the Neoproterozoic: new paleomagnetic data from the Varanger sediments, Northern Norway
14:30-14:50	*Coffee break at "Poster Hall"*	
	Session C4: Paleo-Mesozoic supercontinents… Chair: Juha Karhu	
14:50-15:10	Jüri Plado et al.	Magnetism of tilted Middle Ordovician carbonate sequence in Northeastern Estonia
15:10-15:30	Jussi Heinonen et al.	The Jurassic mafic and ultramafic dikes of Antarctica: implications for Gondwana break-up processes and mantle sources of Karoo continental flood basalts
15:30-17:00	Panel Discussion	
17:00	Closing remarks	
19:30	Farewell dinner in Park Hotel Käpylä	
21:15	Farewell party continues in "Pub Rodinia" (Park Hotel upstairs)	
Saturday , Sep. 29	**Return to home**	

THE DETRITAL ZIRCON RECORD: SUPERCONTINENTS, PARALLEL EVOLUTION – OR COINCIDENCE ?

Tom Andersen[1]

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The interpretation of detrital zircon data is facing some important and potentially damaging inconsistencies that are commonly overlooked: Combined U-Pb and Lu-Hf data from detrital zircon in sedimentary rocks have been used successfully to study global processes such as the extraction, growth and preservation of continental crust (e.g. Belousova et al. 2010), suggesting generally similar patterns of evolution of different continents. Yet at the same time, such data are increasingly used to identify the source-rocks of individual clastic deposits (e.g. Lahtinen et al. 2002), based on the implicit assumption that material from different source terranes carry distinct provenance signatures.

For example, Precambrian detrital zircon age-fractions from late Mesoproterozoic to Phanerozoic sedimentary rocks in Greenland have patterns of U-Pb ages and initial Hf isotope composition indistinguishable from that of zircon from granitoids in Fennoscandia. Although geological considerations suggest that detritus was almost certainly derived from sources within Greenland, the overlap suggests that detrital zircons cannot be used as a general tool to distinguish between sources east and west of the North Atlantic. This is perhaps not surprising, as Fennoscandia and Laurentia (including Greenland) have been near neighbours in three supercontinents (Columbia, Rodinia, Pangea). Transport and homogenization of clastic material in intracontinental basins and along a common continental margin would smooth out differences, and the two neighbouring continents may have closely parallel histories of internal growth.

It is stronger reason for concern that Precambrian age fractions in detrital zircon suites from areas as distant as Australia and Southern Africa also show distribution patterns that cannot be distinguished with confidence from sources in Fennoscandia. These continents have not been near neighbours in post-Archaean supercontinents. Since exchange of detritus between such distant blocks is improbable, one is left with the alternative explanations of pronounced parallel evolution (perhaps mainly related to the assembly of supercontinents in the geological past), or pure coincidence. Ruling out the unattractive possibility of coincidence requires larger sets of data and more rigorous statistical methods that are commonly applied in detrital zircon studies.

Whatever the explanation: Exchange, parallelism or coincidence, observations such as these question one of the main assumptions underlying the use of zircon as an indicator of sedimentary provenance: *That a given age and initial Hf isotopic pattern of a population of detrital zircons can be related to a specific first-generation source* (e.g. Fedo et al. 2003).

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RELATIONSHIP AMONG SUPERCONTINENT ASSEMBLY, SUPERPLUME EVENTS, AND SECULAR TRENDS IN VMS AND IRON FORMATIONS

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Recurrent association in the Precambrian between superplume events and Iron Formation deposition has been known for some time (Isley and Abbott, 1995; Condie et al., 2001; Barley et al., 2005). Recently, their temporal relationship in the Precambrian and Phanerozoic with VMS deposits was also established (Bekker et al., 2010). The link is obvious: hydrothermal systems are more extensive, vigorous, reducing, and metal-rich during LIP emplacement. As a result, larger volumes of metals were released from volcanic rocks and vented to the ocean floor, where massive sulfide deposits formed; ocean redox state was lowered by enhanced flux of reductants (e.g., Fe, Mn, and H_2); and Fe with Mn were delivered by plumes to shallow-water settings where they precipitated forming iron- and manganese-rich sediments. However, peaks in tonnage of VMS deposits are typically also associated with time intervals when supercontinents were assembled since VMS mineralization hosted by bimodal volcanic rocks in back-arc basins has a higher preservation potential in the rock record. Considering that mantle plumes are relatively common throughout the Earth history, it remains uncertain why superplumes and associated mineralization are genetically linked with the early stages in the supercontinent assembly. The association is however striking and repetitive at ~2.74-2.69 Ga, 2.5-2.45 Ga, 2.05-2.06 Ga, 1.88 Ga, 1.1 Ga, and 0.5 Ga when Kenorland, Vaalbara, Nuna, Zimvaalbara-São Fransisco, Rodinia, and Gondwana supercontinents were assembled (cf., Huston et al., 2010). It is proposed herein that external ocean closure during the early stage of supercontinent amalgamation dramatically changed the heat budget of the mantle, leading to mantle overturn, superplume events, and eventually development of new mantle convection pattern. As a result, superplume-initiated rifting at the time when external oceans contracted allows for plate tectonics to persist without interruption in the aftermath of the supercontinent assembly.

PALEOMAGNETIC STUDY OF THE 1.98-1.96 Ga SURUMU GROUP FROM NORTHERN BRAZIL: THE PALEOPROTEROZOIC AMAZONIAN CRATON APW PATH AND PALEOGEOGRAPHIC IMPLICATIONS

Franklin Bispo-Santos[1], Manoel S. D'Agrella-Filho[1],
Ricardo I.F. Trindade[1] and Nelson J. Reis[2]

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2. Serviço Geológico do Brasil, Manaus, Amazonas, Brasil

A paleomagnetic study was performed on 225 cylindrical cores from 39 sites of acid to intermediate volcanic rocks from the 1.98-1.96 Ga Surumu Group (Amazonian Craton). AF and thermal treatment revealed northwestern directions with moderate downward inclinations on samples from 20 of the analyzed sites (Figure 1). Site mean directions cluster around the mean D_m=298.6°; I_m=27.4° (α_{95}=10.1; K=12.1), which yielded a paleomagnetic pole (SG) at 234.8°E; 27.4°N (A_{95}=9.8°). Magnetic mineralogy studies indicate that ChRM directions were mainly carried by high-coercivity and high-unblocking temperature, SD/PSD magnetites, although for some samples (acid rocks) hematite is also the main magnetic carrier. The Surumu rocks are cut by Mesozoic (c. 200 Ma) mafic dykes. A positive baked contact test was obtained for one of these dykes cutting acid rocks from the Surumu Group, which attests the primary nature of the dyke's magnetization and also, that the Surumu mean characteristic remanent magnetization (ChRM) direction was not affected by this younger magmatic event.

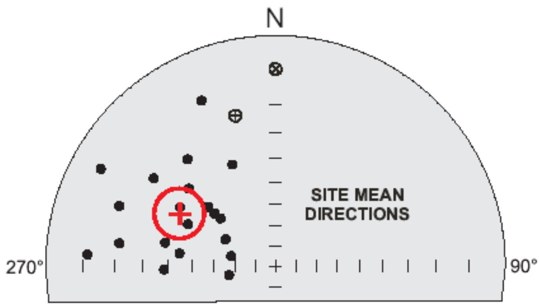

Figure 1. Site mean directions for the Surumu Group. Plus signal (and respective confidence circle - α_{95}) in red indicates the mean of site mean directions calculated for the Surumu Group. ⊕ - present geomagnetic field; ⊗ present geomagnetic dipolar field. Solid (open) symbols represent downward (upward) inclinations.

The Surumu pole is used to better constrain the APW path traced for Guiana Shield for the time interval between 2070 Ma and 1960 Ma (Théveniaut et al., 2006). Comparison with the APW path traced for the West Africa Craton for the same time interval (Nomade et al., 2003) permit to test the paleogeography where proto-Amazonian Craton and West Africa were part of the same tectonic block at 2000-1970 Ma ago (Figure 2). In this reconstruction,

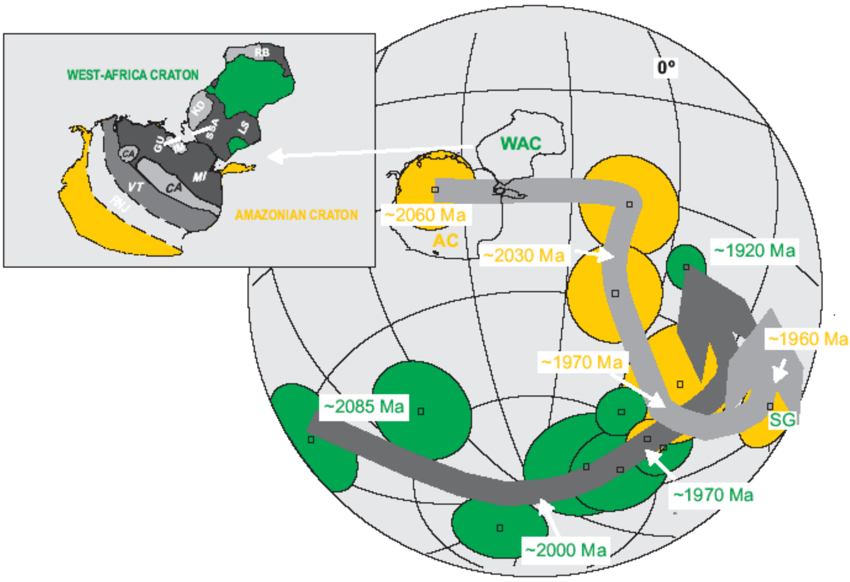

Figure 2. Comparison of the APW paths constructed for the Amazonian Craton (AC) and West Africa Craton (WAC) between ~2080 and ~1920 Ma. Poles from Amazonia (in yellow) and from West Africa (in green) are described in Théveniaut et al. (2006) and Nomade et al. (2003), respectively. Amazonian Craton in its present position; West Africa and respective poles rotated using the Euler rotation pole: 43.3°N; 330.5°E (-71.5°). Inset: Possible paleogeography of Amazonia (Guiana Shield) and West Africa at 1970 Ma ago. CA – Central Amazonia; MI – Maroni-Itacaiunas; VT – Ventuari-Tapajós; RNJ – Rio Negro-Juruena; IM – Imataca Complex; GU – Guri Lineament; LB – Leo Shield; KD – Kenemanan Domain; RB – Requibat Shield; SSA – Sassandra lineament. These lineaments were aligned at that time.

the Guri (in Amazonian Craton) and the Sassandra (in West Africa Craton) shear zones are aligned as suggested by other authors (Onstott and Hargraves, 1981, Nomade et al., 2003, Evans and Mitchell, 2011).

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THE 1.8-1.78 Ga AVANAVERO MAGMATISM - PALEOMAGNETIC EVIDENCE FOR THE SAMBA (SOUTH AMERICA AND BALTICA) RECONSTRUCTION IN COLUMBIA SUPERCONTINENT

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The Avanavero magmatic event spreads over a large area in northern Amazonian Craton (Guiana Shield), including expositions in northern Brazil, Venezuela and Guyana. It forms a large igneous province (LIP) represented by a series of dykes, thick sills and small plugs of variable composition. Seven accurate U-Pb determinations yielded ages between 1794±4 Ma and 1780±8 Ma for dykes and sills from Brazil and Guiana (Santos et al., 2003; Reis et al., 2012). A mean age of 1788.5±2.5 Ga was calculated which is considered the best age of this magmatism. In Brazil, the Avanavero dykes and sills intrude the Volcanic and sedimentary rocks from the Surumu Group and the Roraima Supergroup, respectively.

A paleomagnetic study was performed on cylindrical cores from 19 sites of the Avanavero sills and dykes located in the northern area of the Roraima State (Brazil). AF and thermal treatment revealed southeastern directions with low downward/upward inclinations on samples from 13 out 19 analyzed sites. Site mean directions cluster around the mean D_m=138.2°; I_m=-3.4° (α_{95}=13.0; K=11.1), which yielded a paleomagnetic pole at 27.9°E; 48.4°S (A_{95}=9.6°). Magnetic mineralogy studies indicate that ChRM directions were mainly carried by high-coercivity and high-unblocking temperature, SD/PSD magnetites. A positive baked contact test was obtained for one of the sills cutting sedimentary rocks from the Roraima Supergroup, which suggests that the isolated ChRM directions carried by the Avanavero sills and dykes probably represent a thermo-remanent magnetization acquired during cooling of the rocks at ca. 1790 Ma ago. Figure 1 shows a possible Paleoproterozoic paleogeography for Laurentia, Baltica, Amazonian Craton and West Africa Craton (Johanson, 2009; Evans and Mitchell, 2011). In this reconstruction, the Guri (in Amazonian Craton) and the Sassandra (in West Africa Craton) shear zones are aligned as suggested by other authors (e.g., Evans and Mitchell, 2011). The Avanavero pole compares well with the 1790-1780 Ma Baltica mean pole. Also, an 1880-1750 Ma apparent polar wander path traced for Laurentia passes over north geographic pole between 1835 and 1750 Ma corroborating the paleogeography shown in Figure 1, which is consistent with the proto-Amazonian Craton and Baltica link as in SAMBA connection (Johansson, 2009) at 1780 Ma ago in the Columbia Supercontinent.

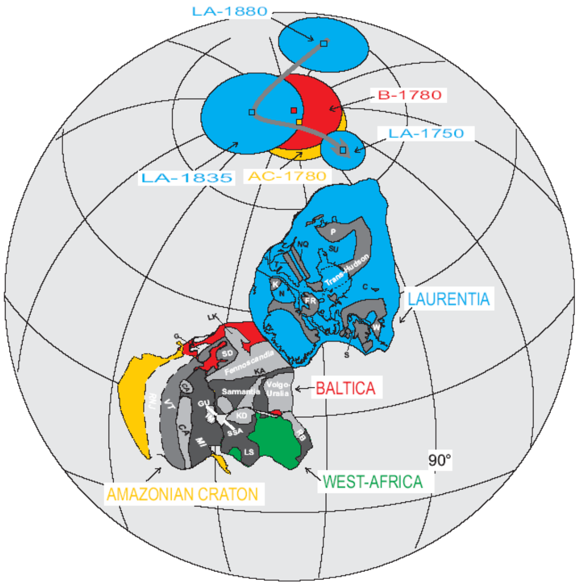

Figure 1. Columbia reconstruction at ~1790-1780 Ma, and selected paleomagnetic poles with their corresponding cone of confidence circles for Baltica (blue), Laurentia (red) and Amazonia (yellow). Euler rotation poles: 19.1°N; 350.0°E; -88.6° (Laurentia); 1.41°N; 306.6°E; -45.8° (Baltica); 56.6°N; 157.5°E; 95.3° (Amazonian Craton); 15.5°N; 188.6°E; 103.0° (West Africa Craton). Symbols as in D'Agrella-Filho et al. (2012)

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1.80-1.75 Ga MAFIC DYKES IN THE UKRAINIAN SHIELD - A KEY TO THE PALEOGEOGRAPHY OF BALTICA WITHIN COLUMBIA

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Despite many recent achievements in the reconstruction of Paleoproterozoic supercontinent Columbia/NUNA (Evans and Mitchell, 2011; Pesonen et al., 2003; Reddy and Evans, 2009; Rogers and Santosh, 2009), it is still far from an entirely satisfactory solution. The experience of reconstructing Mesoproterozoic Rodinia (Li et al., 2008)) has shown that one of the major problems is the imperfect agreement between paleomagnetic data and various geological records. Among the latter, the LIPs (Large Igneous Provinces) with their mafic dyke swarms (Ernst et al., 2008), when dated properly, appear to provide the closest approximations in view of continental block configurations within breaking-up supercontinents. The recognition of LIPs, however, is often under question since mafic dyke swarms can also indicate plate reorganization and tectonic block movements inside still assembling supercontinent. The 1.80-1.75 Ga mafic dykes widely distributed in the Ukrainian Shield of the East European Craton (Baltica), are such an example of the latter (Bogdanova et al., subm.).

The Ukrainian Shield (UkS) comprises the exposed crust of the ca. 2.0 Ga protocraton Volgo-Sarmatia, which together with Archean and Paleoproterozoic Fennoscandian terranes formed Baltica at 1.80-1.75 Ga. 967 mafic dykes related to 1.80 to 1.75 Ga AMCG (=anorthosite-mangerite-charnockite-granite) plutons have been identified in the UkS from geological and geophysical data. Their distribution, orientations and compositions in three different (Volyn, Ingul and Azov) crustal blocks of the UkS are closely related to major strike-slip fault systems developed during two phases of extension (Fig. 1). The 1.80-1.77 Ga, generation of mafic dykes mostly follows NW-trending (ca. 315º) faults corresponding to the intense NE-SW extension (the Submoshorino phase). It consists of olivine dolerites, picrites, camptonites, lamprophyres, kimberlites and other rocks belonging to tholeiitic and jotunitic subalkalic series. The later, 1.76-1.75 Ga, dyke swarms are instead spatially close to the most voluminous AMCG suites of similar age. They were emplaced during the second (Korsun) phase of faulting when all the older strike-slip fault zones were reactivated and transformed to normal faults by EW extension. These dyke swarms trend 30-40º and 300-320º at most, but some are NS oriented.

The overall transtensional tectonic setting of the mafic dyking associated with AMCG magmatism in Volgo-Sarmatia was defined by convergent tectonics and postcollisional collapse of the thickened lithosphere, and mantle delamination coupled with rotations of Volgo-Sarmatia between 1.80 and 1.75 Ga. This agrees with paleomagnetic reconstructions suggesting several rotations of Volgo-Sarmatia (Elming et al., 2010) during its protracted oblique docking to Fennoscandian terranes and Laurentia in the course of the assembly of supercontinent Columbia.

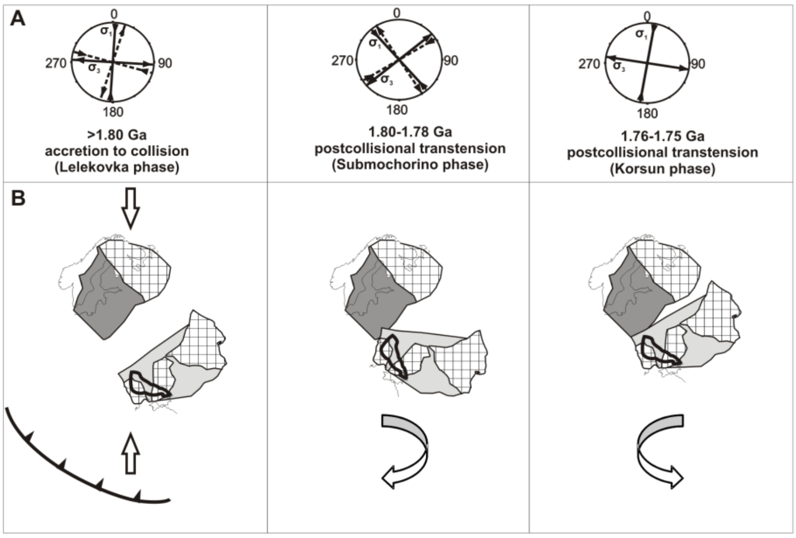

Figure 1. (A) Orientation of the principal stress axes σ_1 and σ_3 during the various phases of strike-slip faulting and mafic dyking in the Ukrainian Shield (Volgo-Sarmatia). Dotted lines indicate possible inversions of kinematics. (B) A tentative model of the rotations of Volgo-Sarmatia between 1.80 and 1.75 Ga during its docking with Fennoscandia. Fennoscandia is shown in a reference position. Archaean blocks are crosshatched, while Palaeoproterozoic belts are marked by the grey colour. The thick hatchured line shows a hypothesized subduction zone (hatchures on the upper plate). The thick solid line marks the Ukrainian Shield.

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THE BASEMENT OF THE SOUTH AMERICAN PLATFORM: HALF LAURENTIAN (N-NW) + HALF GONDWANAN (E-SE) DOMAINS

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The basement of the South American platform comprises two large distinct geologic domains: the Amazonian (NNW, "pre-Brasiliano") and the Extra-Amazônia (E-SE, "Brasiliano"). These domains are separated by a tectonic extrusion line, which is a >4500 km long shear belt that resulted from early Phanerozoic continental escape tectonic processes.

The Amazonian domain comprises Archean nuclei and Paleoproterozoic (Siderian, Rhyacian, Orosirian, Statherian) and Mesoproterozoic (post 1.5 Ga) mobile belts. The mobile belts strike NNW-SSE, indicating crustal growth from NE to S-SW as recorded in the belts themselves, as well by the the anorogenic plutonism.

The extra-Amazonian domain records an orogenic collage, representing a branching system of Brasiliano orogens. The domain includes several minor cratonic nuclei formed of Archean and Paleoproterozoic rocks, amalgamated by mobile belts generated during at least five distinct orogenic processes, from the Eotonian to the Eocambrian. The crust grew following centripetal processes, and the vergence of the mobile belts pointing towards cratonic nuclei. Aside from cratons, several pre-Brasiliano terrains, mainly of Paleoproterozoic age, were also amalgamated, which underwent strong tectonic-thermal reactivations. The presence of Mesoproterozoic mobile belts was not detected so far. When present, all geological records from the Mesoproterozoic and preceding cycles were reset during Brasiliano tectonism. At the end of the Brasiliano orogeny, important post-collisional extrusional tectonics took place, which is responsible for structuring the main Brasiliano provinces and for separating them from the Amazonian domain.

The Amazonian domain, as well as several terrains of the Andean basement, present many compositional affinities and crustal evolution episodes akin to those recorded in the northern, Laurentian continents. The Brasiliano domain displays many compositional, structural and crustal evolution affinities with those from the African continent, that is, Western Gondwana. The more than 4,500 km long NNE-SSW Transbrasiliano lineament between these two domains is the record of a final scenario of important extrusion, following the many collisions, and displays evidence of intense seismic and faulting activity along the Phanerozoic.

TESTING PRECAMBRIAN SUPERCONTINENT RECONSTRUCTIONS WITH PALEOMAGNETIC 'KEY POLE' DATA

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Key paleomagnetic poles are (a) well defined and (b) precisely dated (Buchan 2007). The rock unit from which the pole is derived must have a precise (usually U-Pb) age and the paleopole itself must be demonstrated primary using a rigorous field test. Many hundreds of Precambrian paleopoles have been published, but only a tiny percentage, mostly from mafic intrusions, pass the criteria for a key pole. Only key poles are sufficiently well constrained for use in defining reliable apparent polar wander paths (APWPs), establishing continental reconstructions or testing models of true polar wander (TPW), non-dipole fields, etc.

Basic techniques that use paleomagnetic data to test Precambrian continental reconstructions include: (1) comparing APWPs from different cratonic blocks, (2) comparing individual coeval paleopoles from different cratonic blocks (e.g. Buchan et al. 2000), and (3) comparing the length of great circle arcs between pairs of coeval poles from different cratonic blocks to detect relative motion of the blocks (e.g. Evans and Pisarevsky 2008). All these techniques require the use of key poles. For example, in most instances non-key poles cannot be reliably sequenced along APWPs because of poor dating (uncertainties may be hundreds of millions of years) and magnetic polarity ambiguity. Because of their sheer number, non-key poles often constitute noise which can swamp the tiny number of key poles. Therefore, when APWPs based on key poles are not available (as is usually the case), techniques 2 and 3 should be employed.

Supercontinents have been proposed for several intervals in the Precambrian. The most widely discussed are late Archean-early Paleoproterozoic supercontinents such as Kenorland (or smaller supercratons), and various versions of Columbia/Nuna in the late Paleoproterozoic-early Mesoproterozoic and Rodinia in the latest Mesoproterozoic-Neoproterozoic, although there are numerous other proposals. At present there are far too few key paleopoles to test overall reconstructions, but testing some important elements of Proterozoic reconstructions is possible.

A decade ago only about 25 independent key poles were available globally in the Precambrian (e.g. Buchan et al. 2000, 2001). Most were from Laurentia and one of its predecessors, the Superior craton. Data were only sufficient to permit construction of reliable APWP segments in a few short intervals for Superior craton and Laurentia, and to allow comparison of Laurentia and Baltica at 1.27 Ga and Laurentia and Kalahari at 1.105 Ga. Since that time the number of key poles has doubled with the majority of new poles derived from outside Superior/Laurentia. In addition, paleomagnetic data without primary field tests are available from a significant number of units that have recently been precisely dated, so that there is great potential for establishing many more key poles.

New key poles from Superior craton and Laurentia allow better definition of APWP segments. Key poles are now available from another of Laurentia's predecessors, the Slave craton. When compared with those from the Superior, they demonstrate that the two cratons drifted independently in the mid Paleoproterozoic prior to 1.88 Ga. This in turn confirms that (a) plate tectonic processes were operating at that time and (b) that supercontinent reconstructions that incorporate Laurentia prior to 1.88 Ga are invalid.

New key pole APWP comparisons for Baltica and Laurentia indicate that the arctic margin of Baltica lay adjacent to NE Greenland over the 1.59-1.27 Ga period in the early-mid Mesproterozoic. (This configuration may extend back to 1.83 Ga in the Paleoproterozoic if poles from precisely dated 1.63, 1.77-1.74 and 1.83 Ga units are confirmed to be primary.) Because of its size, this Baltica-Laurentia reconstruction must form an important element of any early-mid Mesoproterozoic supercontinent.

In addition to key poles that define APWP segments, one or more individual key poles are now available from each of a number of major cratonic blocks including Laurentia, Baltica, Australia, Siberia, South China, North China, Kaapvaal, Kalahari, Amazonia, Dharwar, as well as smaller terranes such as Avalonia. They can be useful in testing elements of supercontinent reconstructions using techniques 2 and 3. Occasionally, there are precise age matches. For example, 0.615 Ga key poles from Baltica and Laurentia permit these two blocks to have been together, but in a different configuration then established for the early-mid Mesoproterozoic (see above), 1.11 Ga Kalahari and Laurentia key poles indicate that these two blocks were not adjacent, and 1.88-1.87 Ga key poles from Superior and Kaapvaal cratons establish that they were both at intermediate latitudes. In many other cases, age matches are only approximate, so that conclusions are tentative. For example, approximate key pole age matches are available for North China and Laurentia at 1.77 Ga and 1.74 Ga respectively, and for Amazonia and Baltica at 1.42 Ga and 1.45 Ga respectively.

Finally, various TPW episodes have been postulated during the Proterozoic, based on interpretation of paleomagnetic poles. Unfortunately, as yet, there are no key pole data sets that permit a rigorous test of any of these proposals.

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PETROGENESIS AND CRUSTAL CONTAMINATION OF THE NIPIGON SILLS: A GEOCHEMICAL AND SPATIAL RE-EVALUATION

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A compilation and re-evaluation of 2397 publically available, spatially referenced samples with associated whole-rock geochemistry has yielded previously unrecognized variation within the Midcontinent Rift-related Nipigon sills of the Nipigon Embayment. Nipigon diabase sills represent the most volumetrically significant Midcontinent Rift-related unit in Canada covering an area in excess of 20 000 km2 (Sutcliffe, 1991). 796 Nipigon sill samples have been investigated using Th/Ybpm ratios as a means of evaluating crustal contamination. This investigation revealed three distinct Nipigon sill types comparable to the three distinct suites of sills suggested by Hollings et al. (2007) based on radiogenic isotope data. This discrimination supports the isotopic signatures for each group as higher Th/Ybpm values are consistent with a more negative ƐNd(t=1000Ma)values. Ranges for the three Nipigon sill types are summarized in Table 1.

Table 1. Summary of geochemical data for the Nipigon sills

	Nipigon I	Nipigon II	Nipigon III
Th/Yb_{pm}	1.97 – 3.4	3.4 – 5.0	5.0 – 6.5
Nb/Yb_{pm}	0.75 – 1.65	1.2 – 1.8	1.5 – 2.2
Nb/Nb*	0.425 – 0.65	0.35 – 0.55	0.3 – 0.5
La/Sm_{pm}	1.2 – 1.8	1.60 – 2.0	2.2 – 2.6
Gd/Yb_{pm}	1.0 – 1.9	1.0 – 1.9	1.0 – 1.9
εNd(t=1000Ma)	-0.5 to -1.5	- 1.5 to - 3.0	> - 5.0

Populations of more-contaminated samples (Nipigon types II and III) dominantly lie within two areas (Fig. 1); a north-trending, linear group in the southwestern Nipigon Embayment and an arcuate array in northern and eastern Lake Nipigon. Nipigon sill types II and III display higher Th/Ybpm values, lower Nb/Nb* values and more negative ƐNd(t=1000Ma) values when compared to Nipigon sill type I. These populations appear to be proximal to major structures such as the Black Sturgeon fault, southwest of Lake Nipigon, (Fig. 1). Type I Nipigon sills are located peripherally to Nipigon sill types II and III and display lower Th/Ybpm values, higher Nb/Nb* values and less negative εNd(t=1000Ma). Type I Nipigon sills do not appear to be related to any known major structures.

Preliminary analyses show that Archean rocks of the Quetico Subprovince appear to control the Th/Ybpm values, whereas Sibley Group sedimentary rocks have a stronger control on Nb/Nb*. Type II and III Nipigon sills display higher Th/Ybpm values than type I sills, consistent with the model in which type II and III sills have assimilated metasedimentary rocks of the Quetico Subprovince. The higher Nb/Nb* values of type I Nipigon sills likely reflects a greater degree of interaction with the rocks of the Sibley Group suggesting shallower level contamination (as the Sibley is not present at depth within the Nipigon Embayment). The more crustal-contaminated nature of type II and III sills in conjunction with their proximity to major structures, suggest that magmas feeding these sills ascended through structures that provide more interaction with Quetico rocks at greater depths. This is supported by type II and III samples showing more negative εNd(t=1000Ma) values than type I samples, a signature that infers interaction with older continental crust. The source magma

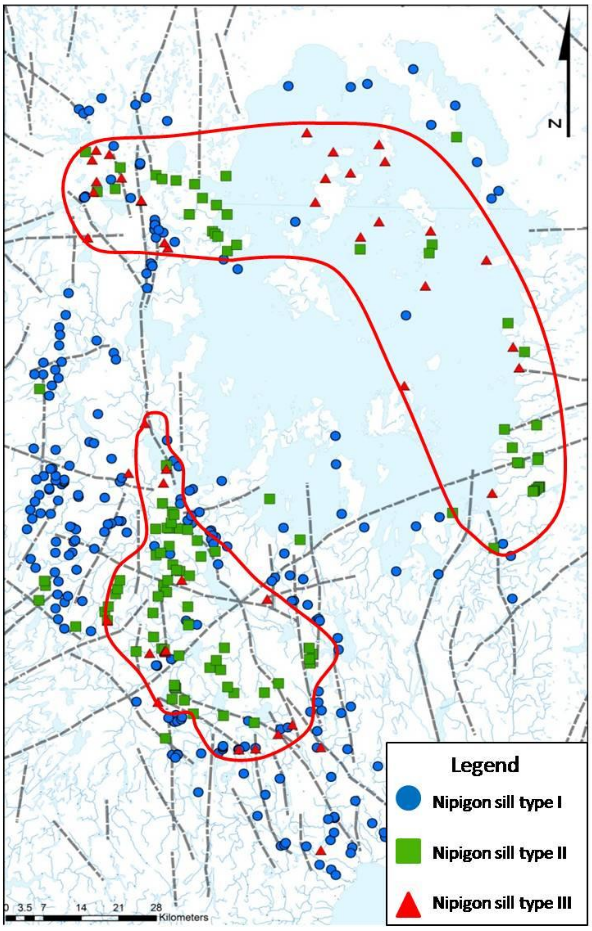

Figure 1: Map of the Nipigon Embayment showing the distribution of Nipigon sill types I, II and III with contamination centres outlined in red. Major faults after Hart and MacDonald (2007).

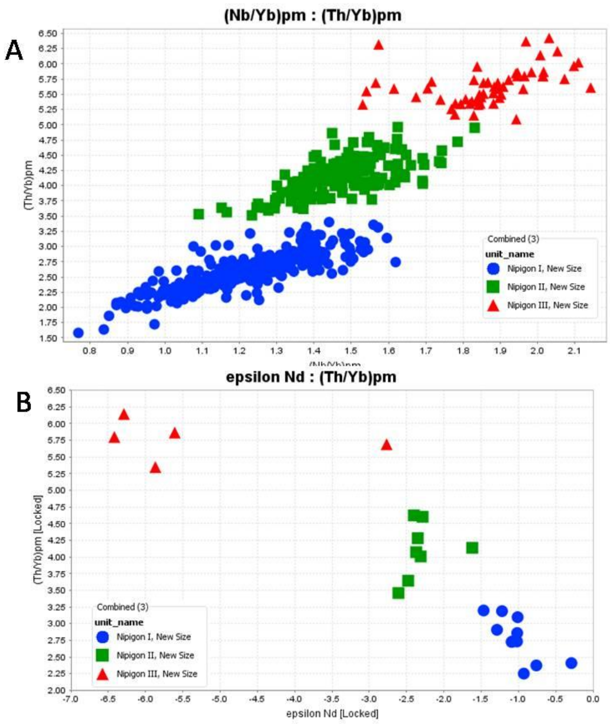

Figure 2: A) Nb/Yb_{pm} vs. Th/Yb_{pm} plot; B) $\varepsilon Nd_{(t=1000Ma)}$ vs. $Th/Yb_{pm.}$ Radiogenic isotope data from Hollings et al. (2007), Normalizing values from Sun and McDonough (1989).

feeding type I Nipigon sills possibly exploited the same pathways yet had less interaction with continental crust at depth as the system was armoured by previously ascended magmas. As type I melts were laterally emplaced, they were contaminated by Sibley Group sedimentary rocks as displayed by elevated Nb/Nb* signatures.

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GEOCHEMISTRY AND PAELOMAGNETISM OF THE DEVON TOWNSHIP BASALT, ONTARIO, CANADA

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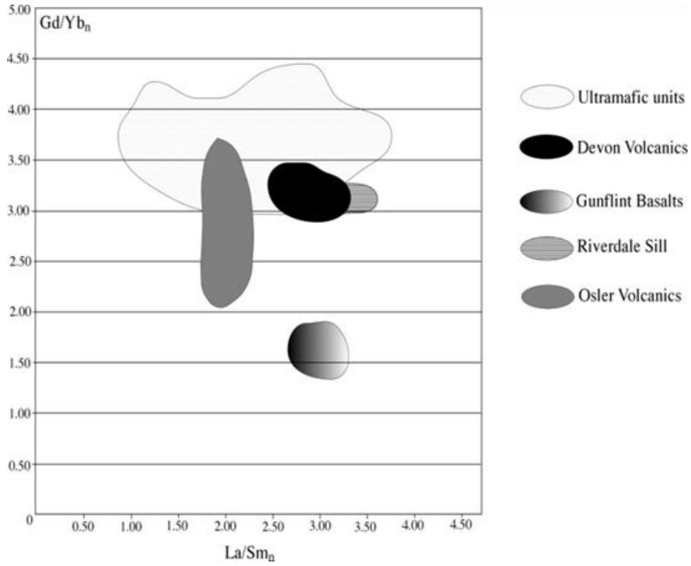
A unit of mafic rock in Devon Township, south of Thunder Bay, was mapped by Tanton (1931) and was termed Rove Formation Basalt. The results of this study have led to it being renamed the Devon Volcanics. The 4 to 6 m thick unit is exposed on a plateau 9 km long and 0.8 to 1.0 km wide and is in apparent conformable contact with the underlying shales of the Paleoproterozoic Rove Formation. A pronounced chilled margin at the base of the flow consists of variolitic material up to 20 cm thick. The flow-top also exhibits a variolitic texture up to 15 cm thick. The presence of ropy flow top and amygdules, as well as quench textures, support a volcanic origin.

The Devon Volcanics are basalts to basaltic andesites and plot in the basaltic trachy-andesite to trachy-andesite fields on a TAS diagram. Rare-earth element geochemistry shows the unit to be relatively enriched in both HREEs and LREEs, comparable to modern Ocean Island Basalts, but also display a negative Nb anomaly, most likely the result of lower crustal contamination. The basalts are similar to the ultramafic sills of the Nipigon Embayment as well as the Riverdale Sill (Hollings et al., 2007 and 2010; Fig. 1). $\varepsilon Nd(t=1100Ma)$ values of -2.89 and -3.48, are consistent with contamination by a lower crustal source. The trace element and isotopic character are similar to that of basalt type II composition (Nicholson et al., 1997) suggesting that it was emplaced early in the Midcontinent Rift history, correlative with the Upper Siemens Creek Volcanic Group, the Central Suite of the Osler Group and some of the Ely's Peak Basalts.

The characteristic paleomagnetic mean direction of three sites from the Devon Volcanics is typical Keweenawan reversed (D=110.5º, I=-67.6º, $\alpha95$=12.4º, k=99.6). The primary nature of this direction is supported by a tentative positive baked contact test against the Rove shale. A secondary low coercivity component is also observed (the mean: D=294.8º, I=42.6º, $\alpha95$=41.4º, k=9.9, N =3). The paleomagnetic pole (46.4ºN, 211.6ºE, A95=18.7º) plots close to the other Keweenawan reversed paleopoles (Fig. 2), but we note that being obtained from a single cooling unit, our data does not adequately average out paleosecular variation.



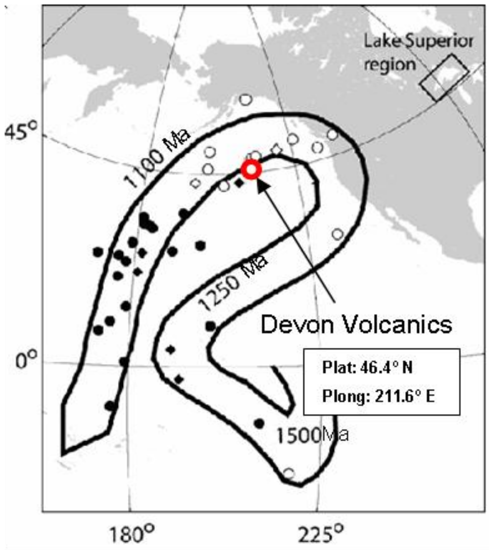


Figure 1. Gd/Yb$_n$ versus La/Sm$_n$ showing comparison between the Devon Volcanics and other Midcontinent rift-related units. The fields are from Hollings et al. (2007 and 2009).

Figure 2. The Devon Volcanics paleopole superimposed on the Logan Loop. The open (closed) symbols indicate reversed (normal) polarity.

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PRECISELY DATED IMPACT STRUCTURES AND THEIR USE IN SUPERCONTINENT RESEARCH

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Understanding the evolution of planet Earth in Precambrian times critically relies on models that reconstruct movement of continents, cratonic blocks, and separated terranes. Tools used in such reconstructions comprise the correlation of features such as orogenic belts, rifts, major lineaments, dyke swarms, large igneous provinces, ophiolite occurrences, and lithostratigraphic data (see Zhao et al. 2002; Pesonen et al. 2003). The fix points in the "game of moving continents" are provided by paleopoles measured on precisely dated rocks that are mostly mafic dykes.

Currently, ~180 terrestrial impact structures are known (EarthImpactDatabase), ranging from the recent 14-m-sized simple crater Carancas, Peru (Kenkmann et al. 2009) to the largest and oldest known complex impact structure Vredefort, South Africa. While general principles of dating terrestrial impact events are well constrained (Deutsch and Schärer 1994), substantial recent progress in dating techniques has raised the interest in craters for supercontinent research. This is due to the fact that impact structures may contain "impact melt" lithologies (melt rocks, suevites) suited for paleomagnetic studies (e.g., Plado and Pesonen 2002). U-Pb age dating even on fragments of single zircons in combination with EBSD (e.g., Timms et al. 2012) allows unravelling the history of the target and determination of the shock age. Shocked zircons can survive fluviatile transport for hundreds of km, deposition and re-deposition, and geologic events in a time segment of more than 2 billion years (Cavosie et al. 2010). In general such advanced studies can also be applied to micro-baddeleyites occurring in mafic dyke rocks. Similarily, high precision ^{39}Ar-^{40}Ar dating on small quantities of impactites yielded highly reliable age data for a number of craters (Jourdan et al. 2012). Precise dated impact craters can provide precise paleo poles.

Jourdan et al (2012) list only 18 impact structures dated with a precision better than ±2%. Of those three originated in Pre-Cambrian times (Keurusselkä, Finland – 1059 Ma; Sudbury, Canada and 1849.3 Ma; Vredefort – 2023 Ma, South Africa). In addition, several spherule layers, i.e., distal ejecta layers similar to the world-famous K-T event deposit, have been identified in Australia and South Africa. They are fairly well bracketed by U-Pb ages on zircon and date back to the Early Archean (Glass and Simonson 2012). Plotting these impact structures and ejecta deposits on paleomaps could help to better define paleogeography as well as to identify the respective source region (=crater) of the spherule layers. A different aspect of plotting a well dated impact crater in the correct paleoposition was given by Tohver et al. (2012) for the 254.7-myrs.-old Araguainha structure, Brazil, by highlighting the maximum radius of destruction caused by this impact event.

At the symposium we will present a current status of terrestrial impact structures with examples on how they can be used in constraining paleomagnetically constructed supercontinent assemblies.

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THE PALEOGEOGRAPHY OF PANGEA: PROGRESS AND PROBLEMS

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When considering the paleogeography of Rodinia, and supercontinents from even deeper time, it is important to keep in mind that the paleogeography of the most recent supercontinent, Pangea, is still not entirely established. Recently, significant progress has been made in the reconstruction of Laurasia and West Gondwana, most notably in that their long-disparate paleomagnetic data have been shown to be affected by widespread data-artifacts. With the implementation of inclination-shallowing corrections and the most up-to-date Euler parameters, the paleomagnetic data have been demonstrably reconciled with the conventional (A-type) reconstruction of Laurasia and West Gondwana. But, despite this important step forward, serious reconstruction problems in East Gondwana and the Tethys remain unresolved. In East Gondwana, late Paleozoic—Mesozoic paleomagnetic data from Australia are consistently incompatible with coeval results from Laurasia and West Gondwana, assuming an A-type paleogeography. There is no geologic evidence to support an alternative reconstruction of Australia relative to West Gondwana. However, the paleomagnetic discrepancy cannot be explained in terms of poorly known Euler parameters or inclination shallowing, and so remains a troubling enigma. The late Paleozoic—Mesozoic history of the Tethyan realm is a notoriously complex system of polyphase terrane migrations, that has yet to be reconstructed in a self-consistent and temporally-continuous way. As the history of this realm describes the construction of most of Central and East Asia, a working understanding of its kinematic evolution is of fundamental importance. Here we more fully explore the recent progress made in the reconstruction of West Pangea, the problems that remain in East Pangea, and some preliminary results of new efforts intended to resolve the latter.

SYMMETRIC AND ASYMMETRIC REVERSALS IN THE 1.1 Ga CENTRAL ARIZONA DIABASES: THE DEBATE CONTINUES

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The position of continents in the onset of the Rodinia supercontinent is quite well established by paleomagnetic data. Yet, the fit of Laurentia with the other continents is a matter of debate, mainly due to the fact that asymmetric reversals is observed in some ~1.1 Ga rocks from Lake Superior, Central Arizona and Grand Canyon. Several mechanisms to explain this asymmetry have been proposed: i) non-averaged secular variation, ii) remagnetization, iii) rapid continental drift and iv) non-dipole contribution (e.g. Pesonen and Nevanlinna, 1981 and references therein). Swansson-Hysell et al. (2009) have recently argued that the ~1.1 Ga volcanic sequence at Mamainse Point, Lake Superior, consists of apparent polar wander (R2l→N2u), followed by two symmetric reversals (R2u→N1, N1→R1).

For the study we selected 33 sites from diabase sheets in Central Arizona, previously dated about 1150-1080 Ma. We performed detailed paleomagnetic and rock magnetic investigations, together with U-Pb datings, optical and scanning electron microscopy measurements. The analysis of individual sites shows two distinct polarities, with an asymmetry (R→N) similar to that observed previously by Harlan (1993) and Sandberg and Butler (1986) but larger than that observed in Lake Superior rocks. We indicate in Fig. 1a the normal polarity mean as N1 (N= 13 sites, D=274.8˚, I=38.7˚, α_{95}=7.6˚) and the reversed one as R2 (N=5, D=193.7˚, I=-78.7˚, α_{95}=15.7˚). Our analysis further reveals one site (DF) with a normal steep inclination (N2: D=332.6˚, I=69.4˚, α_{95}=3.5˚), and one site (SD) with a reversed, moderately shallow inclination (R1: D=95.8˚, I=-35.9˚, α_{95}=7.8˚) thus envisaging symmetric reversals. New age and paleomagnetic data are summarized in Table 1 and Fig. 1. The following conclusions can be drawn:

1. The Arizona R2-dykes appear to have formed around 1115 Ma; they plot distinctly away from their coeval LS poles, however they agree with ~1140-1160 Ma Greenland N-poles.

2. The N2 Arizona direction is symmetric to R2-direction; however, its age (1096±2 Ma) is significantly younger than the age of R2 (1110-1119 Ma). Compared to the age of corresponding LS reversed poles (~1107-1112 Ma), N2 again appears to be much younger.

Table 1. Preliminary U-Pb age data of the Central Arizona diabases

Dyke	Sample	Age ± Δ (2 sigma)	Method	n	Mineral	Pol
ID	ID-4	1119 ± 10	wa 7/6	2	b	R2
DA	DA-1	1085 ± 5.2	wa 7/6	2	b	M (N1)
DA	DA-2	1111.6 ± 8.9	model 1	3	b, z	M (R2)
DF	DF-2	1096.4 ± 2.1	wa 7/6	3	b	N2
FD	FD*	1088 ± 11				N1

b - baddeleyite; z - zircon; wa 7/6 - weighte average $^{207}Pb/^{206}Pb$ date.* Pers. Comm. Ryan Bright

3. One N1-polarity dyke (FD) with an age of 1088±11 Ma (Ryan Bright, pers.comm.) has a pole comparable, or slightly to SW from coeval LS N1-poles.

In summary, the history of the Logan Loop remains complex. A broad age-trend links the two reversal events, nevertheless, the controversial age of event N2-R2, and the discrepancies with the LS ages may indicate the influence of complex non dipolar fields at 1.1 Ga.

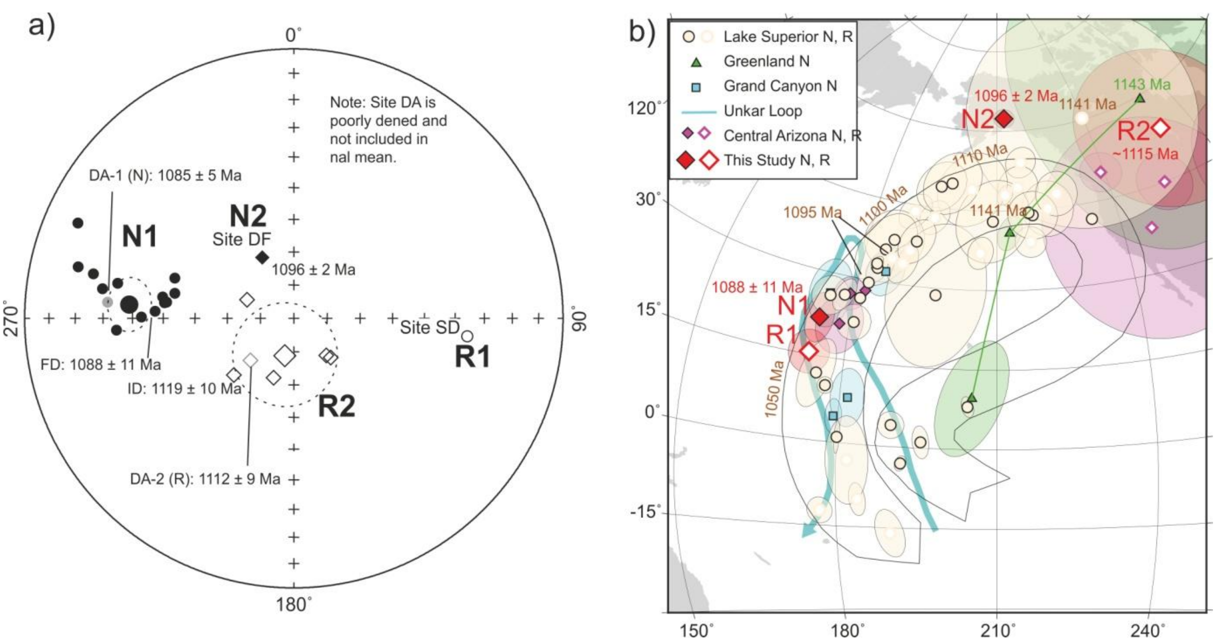

Figure 1. a) Individual sites (small circles and diamonds) yield averages suggesting perhaps two distinct symmetric reversals (large circles: N1, R1; and large diamonds: N2, R2). Equal area projection. b) Logan Loop (dashed arrow) showing the final averages from this study (red diamonds), and other available studies from Central Arizona (magenta diamonds) the Grand Canyon (cyan squares, and thick cyan line denoting the Unkar Loop), Lake Superior (beige circles), and Greenland (green triangles).

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PALEOPROTEROZOIC GRANITOIDS MARKING THE SIBERIAN CRATON AND PRE-RODINIA SUPERCONTINENT ASSEMBLY

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The Siberian craton was assembled in the Paleoproterozoic by collisions of Archean (Tungus, Anabar, Aldan, Stanovoy) and Paleoproterozoic (Olenek) superterranes (e.g., Rosen, 2003; Gladkochub et al., 2006). Archean superterranes consist of smaller terranes, each of them have its own scenario of development (Gladkochub et al., 2009). The ca. 2.5 – 2.4 Ga collisional and anorogenic granitoids mark the final amalgamations of some Archean terranes. There was no igneous activity in these amalgamated terranes between ca. 2.4 – 2.2 Ga. Some minor ca. 2.2 – 2.1 Ga anorogenic intrusions are locally distributed within some terranes, e.g, ca.2.1 Ga alkaline granites were emplaced in the Olekma terrane of the Aldan shield (Larin et al., 2002). This (ca. 2.4 – 2.1 Ga) relatively quiet period has been followed by a major ca. 2.1 – 2.0 Ga magmatism. Igneous complexes of this age have been found in active margins of Archean terranes still separated by oceanic crust, and within Paleoproterozoic island arcs. Various 2.06 – 2.00 Ga volcanic rocks and TTG-type granitoids were found in the Aldan shield's terranes in southeastern part of the craton (Anisimova et al., 2006 etc.). The ca. 2.02 Ga active margin related calc-alkaline granites occur within the Goloustnaya terrane of the Akitkan orogenic belt in southern part of the craton (Poller et al., 2005). Ca. 2.02 Ga subduction-related TTG-type granites and calc-alkaline granites were found in the Baikal block of the Akitkan orogenic belt (Larin et al., 2006 etc.). Interestingly, 2.04 Ga post-tectonic granites were found in the Olenek terrane of the northern part of the craton (Wingate et al., 2009). All Archean terranes finally collided and formed the Siberian craton in Late Paleoproterozoic. In global scale this time corresponds to the beginning of the Pre-Rodinian supercontinent assembly (Zhao et al., 2002). The early stage of the Siberian assembly is marked by ca. 2.0 – 1.9 Ga syn- and post-tectonic granitoids (Larin et al., 2006). The timing of the final stage of the Siberian assembly is manifested by ca. 1.88 – 1.84 Ga numerous post-collision granitoids and coeval mafic and felsic volcanics found mainly along the southern Siberian margin (Donskaya et al., 2005; Larin et al., 2003). This magmatic activity was possibly related to incorporation of the Siberian craton into the Paleoproterozoic supercontinent (Didenko et al., 2009).

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CREATING PLATE RECONSTRUCTION MODELS AND ANIMATIONS FOR THE PRECAMBRIAN UTILISING INFORMATION FROM THE IGCP 509 DATABASES AND STRUCTURAL VERGENCE DIRECTIONS TO SUPPLEMENT PALAEOMAGNETIC INFORMATION

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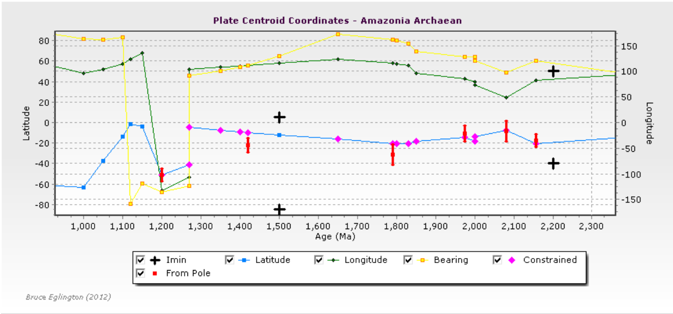
Understanding and visualizing the geology of multiple domains around the world is a challenge. Database systems developed for the IGCP 509 project (Eglington *et al.*, 2009; Eglington *et al.*, 2012) facilitate this process by enabling users to extract information for selected domains and create time-space correlation charts which illustrate lithostratigraphy, geochronology, geodynamic setting, rock class, depositional setting and major dyke events. These criteria, together with the timing and character of metamorphism, deformation and mineralising events, help constrain plate reconstruction models, building on compilations already available from the IGCP 440 project. Considerable information is therefore now available for both the Nuna and Rodinia supercontinents.

Plates for use in the model have been defined or refined utilizing geology, aeromag coverages and the extensive geochronology and isotope compilation in the DateView database. Plate reconstructions are ultimately refined by palaeomagnetic constraints but, as good data are sparse for the Precambrian, a Proterozoic model has been developed using additional plate geometry, structural vergence directions, lithostratigraphy and geochronology. Time-specific reconstructions have been tied together with appropriate plate motions so as to achieve internally consistent patterns of amalgamation and breakup through time. As new palaeomagnetic information becomes available the model will be tested and refined.

GPlates and the Paleogis plugin for ArcMap were used to visualize and modify aspects of the model, but additional software was written to facilitate management of the plate rotation parameters in a MicroSoft Access database and to provide graphs illustrating variations in latitude (both for model and for available palaeomagnetic poles), longitude and plate orientation (Fig. 1). Longitude for the various plates is constrained between major supercontinent nodes, following the suggestions of Mitchell *et al.* (2012). Plate orientation changes are shown relative to a vector originally pointing north at the present day.

Clearly defined variations in igneous and metamorphic activity are apparent across Nuna (Fig. 2), as are spatially distinct mineralisation styles. Both mineralisation clan and geochronology can be uniquely associated with geodynamic setting. Together, available data illustrate the interplay of both collisional and accretionary processes in different parts of Nuna, leading to the preferential



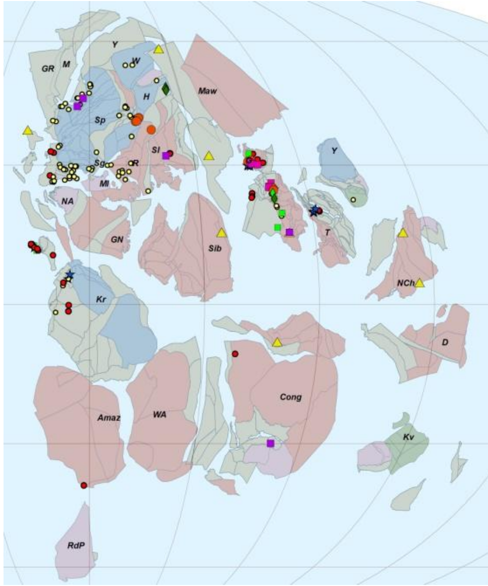


Figure 1. Graphical view of reconstruction model for part of Amazonia.

Figure 2. Reconstruction of parts of Nuna at ~1.6 Ga. Red dots are igneous crystallisation, blue are metamorphic ages and yellow are cooling ages from the DateView database.

preservation of certain deposits in some areas and their absence in others. Animation of the model at 5 Ma increments from about 2100 Ma to 1400 Ma provides useful visual insights into the evolution of Nuna, leading in to Rodinia.

Further development of the model in future will incorporate additional information as it is compiled and new data are published and the model is being extended into the Meso- and Neo-proterozoic and into older Palaeoproterozoic.

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FENNOSCANDIAN 2.7–1.7 GA METALLOGENY AND SUPERCONTINENT CYCLES

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The final stages of the Archaean and all of the Palaeoproterozoic development of the Fennoscandian shield and, hence, most of its major metallogenic features can be connected to supercontinent cycles. The Neoarchaean supercontinent *Nena* (or *Kenorland*, Baltica + Laurentia) was assembled at about 2.75–2.60 Ga, if not before (Mertanen & Pesonen 2012, Strand & Köykkä 2012). That is, it was formed by and during of one of the major continental growth episodes of the Earth's history (Goldfarb et al. 2009). The major trends of metallogeny of the time in Fennoscandia are similar to greenstone terrains elsewhere, just the sizes of the deposits seem smaller than in some other areas: the orogenic gold deposits are abundant but small, the komatiitic Ni occurrences, so far detected, are small and rather scarce, and only very minor VMS deposits have been found (Eilu 2012).

Compared to its assembly in the Neoarchaean, the extended break up of the *Nena*, from about 2.45 to 1.98 or 1.95 Ga, delivered major mineral deposits across the shield. The 2.45–2.39 Ga rifting event, possibly related to a major mantle plume, produced reef-type PGE and Cr, contact-type PGE-Ni-Cu, and massive Cr and V-Ti-Fe deposits in layered intrusions. During ca. 2.40–1.98 Ga, somewhat unusual mafic intrusion-hosted Ni-.Cu±PGE deposits (e.g. Pechenga), the unique Ni-Zn-Cu-Co deposits of Talvivaara type, SEDEX(?) Cu, and clastic sediment-hosted Cu deposits were formed in the shallow-water basins filled with clastic and chemical sedimentary and volcanic rocks. Possibly, the Cu-Zn VMS occurrences which later, during terrane accretion, developed to the Outokumpu Cu-Co-Zn-Ni deposits were formed during the latest stages of rifting. (eg. Lahtinen et al. 2008)

Assembly of the *Nuna* (*Columbia*) took place from about 1.93 to 1.60 or 1.53 Ga. Within the Fennoscandian shield, this assembly is related to the accretional and collisional stages of the Svecofennian (1.93–1.77 Ga) and, possibly, the Gothian (1.68–1.52 Ga) orogenies (Lahtinen et al. 2008, Mertanen & Pesonen 2012). The largest variation in the style of mineralisation within the entire Fennoscandian Shield took place during the formation of the Svecofennian terrain (Eilu 2012). Magmatic arc and microcontinent assembly-related subduction produced numerous VMS-style Cu-Zn±Pb±Ag, porphyry copper, epithermal gold and Kiruna-type Fe±P deposits during 1.93–1.88 Ga. Arc and microcontinent collision are seen the reasons for orogenic gold, orogenic Ni-Cu, and Outokumpu-type Ni at 1.91–188 Ga. The consequent late- to post-collisional stage at 1.88–1.85 Ga produced mafic intrusion-hosted Ti-V-Fe±P deposits. This was followed by a major continent-continent collision stage from 1.84 or 1.82 to 1.79 Ga when perhaps most of the orogenic gold and IOCG deposits were formed. The final post-collisional stage of the composite Svecofennian orgeny at

1.79–1.77 Ga resulted in numerous simple and rare-metal pegmatites. The early stages of the Gothian orogeny brought numerous small intrusion-hosted Ni-Cu and Ti-V-Fe deposits at about 1.68–1.62 Ga.

In detail and in terrain scale, the Fennoscandian mineral deposit types and metallogenic events can be directly related to local plate-tectonic settings and events. In a more wider scale, all these events from ca. 2.7 to 1.7 Ga, from the formation of an individual deposit to an orogenic stage, may be connected to the assembly and break up of the *Nena* (*Kenorland*) and the assembly of the *Nuna* (*Columbia*) supercontinents. These metallogenic events and their relationship to supercontinent cycles are similar to those recorded elsewhere, in other Precambrian terrains (eg., Groves & Bierlein 2007, Goldfarb et al. 2009).

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BASIC DYKES FROM SOUTHERN SWEDEN: PALEOMAGNETIC SIGNATURES, A 935-939 Ma KEY-POLE FOR FENNOSCANDIA AND TECTONIC COHERENCE WITH SOUTHWESTERN SCANDINAVIAN PROVINCE

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The Southwest Scandinavian province (SSp) in the Baltic Shield is separated from the Transscandinavian Granite-Porphyry Belt (TIB) and the Southern Svecofennian subprovince (SSf) in the east by a major deformation zone. During the Sveconorwegian orogeny (Grenvillian; ca. 1150-900 Ma) continent-continent collision resulted in deformation and metamorphism. Ar/Ar hornblende ages indicate deformations as late as ca 915 Ma ago and deformation up to 40 km east of the Protogine Zone, that defines a metamorphic boundary, has been demonstrated. Palaeomagnetic data older than ca 900 Ma from southwestern Sweden should therefore be used with caution, i.e. it must not necessarily represent the Baltic Shield as a hole. Palaeomagnetic results from 935 Ma mafic dykes in the Southwestern Scandinavian province, west of the Protogine Zone, was presented by Pisarevsky and Bylund (2006). Here we present paleomagnetic results from different generations of dykes in the SSf east of the Protogine zone and a new key-pole for the Baltic Shield. One pole from the SSf fulfills a field test for original magnetization and a well constrained Ar/Ar age of 939±3 Ma has been determined from dating of two dykes. This pole is not significantly different from the ca 935 Ma pole of the Southwest Scandinavian province, indicating that there is no or only minor tectonic difference between the SSp and the SSf since 935 Ma. By combining the two sets of poles a new 935-939 Ma key-pole for Baltica is presented. This key-pole also forms an important input to the discussion of the shape and timing of the Sveconorwegian APWP loop.

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CONSTRAINTS FROM THE LIP BARCODE RECORD AND ASSOCIATED GIANT DYKE SWARMS FOR SUPERCONTINENT RECONSTRUCTIONS: PROGRESS REPORT ON THE LIPS-SUPERCONTINENT PROJECT

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We have established an industry consortium project with academic and government support (>$2M) for the "Reconstruction of Supercontinents Back To 2.7 Ga Using The Large Igneous Province (LIP) Record: With Implications For Mineral Deposit Targeting, Hydrocarbon Resource Exploration, and Earth System Evolution" (www.supercontinent.org). Specifically we have the resources to essentially date every regional dolerite dyke swarm and sill province around the world using the U-Pb method. Five global mining companies and one oil company are our primary sponsors in recognition of the importance of LIPs in global resource exploration:

1) LIPs have a direct magmatic link to a host of world-class ore deposits: the largest Ni-Cu-PGE deposits are linked with the mafic-ultramafic component (e.g., Noril'sk, Bushveld); essentially all layered intrusions are part of the plumbing system of LIPs. Also the felsic component can be linked with various commodities (e.g., the Gawler Range bimodal LIP with the Olympic Dam IOCG, iron-oxide copper gold deposit, of the South Australian craton). Carbonatites are strongly linked with LIPs and are the key source of Nb, Ta, and REEs. The link between LIPs and kimberlite fields is also strong, both temporally and spatially.

2) LIP magmatism can have an indirect influence on resources. The associated thermal pulse into the lithosphere can drive hydrothermal fluids and remobilize many different commodities (e.g., Au, U, Hg, etc.). For the oil industry, LIPs are linked to oceanic anoxia producing black shales (hydrocarbon source) in the ocean; they are linked to the subsidence and thermal history of sedimentary basins; and igneous sills can represent both structural traps and (or) reservoir rocks for oil.

3) Industry is keenly interested in robust reconstructions that will allow tracing of metallogenic belts between crustal blocks.

LIPs and particularly their regional dolerite dyke swarms are ideal for reconstructing supercontinents because of their large footprint (often millions of sq. km.); they are commonly emplaced over short periods of time (e.g., less than 1-2 myr), and are associated with breakup. Each major crustal block ('puzzle piece') may be characterized by a unique LIP record that can be represented by and thought of as a "barcode". Comparison of magmatic barcodes between blocks represents a robust tool for identifying nearest neighbors in global reconstructions. Additional criteria, based on paleomagnetism of LIP units and from restoring the primary geometry of radiating dyke swarms, can allow allow definitive reconstructions.

Prior to this project, the magmatic barcodes for Laurentia and Baltica were the best developed. With industry support our project team has produced 49 U-Pb ages in Year 1 and 40 U-Pb ages in Year 2, from crustal blocks around the world. This has allowed us to begin to produce robust barcodes for the West African craton, Amazonia, Siberia, etc., and remarkable links are starting to emerge.

The structure of the project is designed to be a win for the broader community. Our core team of geochronologists, and associated paleomagnetic and geochemistry expertise, is augmented by an informal network of about 50 colleagues around the world who provide kg-sized samples of coarse grained dolerite/gabbro for U-Pb dating from key dolerite/gabbro units in their regions. In return, our geochronology team produces U-Pb ages (mainly on baddeleyite). In collaboration with our regional experts we prepare short reports for our sponsors with the new results and implications for metallogeny and reconstructions. Each report and age result has a one-year confidentiality period to allow our sponsors to utilize this information to their competitive advantage, in return for their considerable financial investment. After the confidentiality period expires, results can be worked up into a full paper and submitted for publication. The array of publications and first author selections are designed to distribute the benefits widely among the community.

We welcome additional collaborators, particularly those with access to samples in remote areas from key crustal blocks. Our work is synergistic with other reconstruction efforts in the community and together we expect to be able to achieve the dream of completing the plate tectonic revolution and producing robust reconstructions back to 2.7 Ga in the next 5-10 years.

5000 KM OF INTERCONTINENTAL SHEAR ZONE: THE TRANSBRASILIANO-KANDI LINEAMENT IN BRAZIL

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The Transbrasiliano lineament is a continental-sized discontinuity exposed between the Amazonian craton and the eastern portion of the South American Platform and is one of the more spectacular intra-continental deformational strike slip systems wordwide. It is over 3,000 km long, extending from Paraguay, across the Tocantins Province and the Phanerozoic Paraná and Parnaíba basins, to the Ceará Atlantic coast. In the context of West Gondwana, this continental structure extends to the African continent along the Kandi/4^{o}30 lineament. Its NE-SW trend is marked by strong magnetic anomalies within the crust and by low S waves velocities in the mantle, suggesting lithosphere thinning. On the surface the lineament is characterized by of a set of N20-50E Late Neoproterozoic ductile right-lateral shear zones, reactivated during the Mesozoic, and also controls aligned drainage and ridge systems during the Cenozoic. Over the years the lineament has been interpreted as a mega-suture active during Gondwana amalgamation, or as the result of post-collision shearing stages. Fault reactivation controlled graben formation, sediment accumulation and magmatism of the Jaibaras basin in NW Ceará, as well as depocentres within the Paraná and Parnaíba basins, and influenced sedimentation at the Atlantic coast. Although a direct link with the lineament has not been established, nearby areas are the sites of seismic activity in NW Ceará and in central Brazil.

Interpretation of airborne geophysical and remote sensing data shows that the Transbrasiliano lineament is comprised of a system of ductile shear zones, forming parallel sets of faults penetrating below the large Paraná and Parnaiba intra-cratonic basins. Dominant direction is N45E, connected with splays of E-W and N-S secondary lineaments. Magnetic lineaments developed along boundaries of crustal/lithospheric blocks. The magnetic lineaments continue below the Phanerozoic basins, where brittle faults characterize several Cambrian to Cenozoic tectonic reactivation events. The results stress the outstanding role of the Transbrasiliano lineament in the tectonic framework of the Brazilian continental lithosphere and its relevance in the evolution of large Phanerozoic intra-continental basins.

MESOPROTEROZOIC WESTWARD GROWTH IN THE SW AMAZONIAN CRATON: RECENT ADVANCES ON GLOBAL CORRELATIONS WITHIN A MIDDLE-PROTEROZOIC SUPERCONTINENT

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The western part of the Amazonian Craton, like the Grenville Province, is a multi-orogen region formed between 1.8 and 0.93 Ga where successive magmatism, metamorphism and deformation occurred, that regionally affected and reworked precursor provinces, producing new complexes, as well as, new juvenile continental crust. Instead, we will briefly summarize the points that deserve consideration as evaluation of Proterozoic continental reconstructions evolves.

The period between 1.79 Ga to 1.74 Ga is characterized by magmatic activity comprised of the Alto Jauru intrusive suite 1.75 Ga juvenile accretionary province, coeval with many other orogenic belts or provinces around the world. In Baltica (Fenoscandian) and in Laurentia (Penokean) importants orogenies are reported to this period of time.

Magmatism and orogensis between 1600 and 1500 Ma is relatively uncommon globally, but it is present in Mato Grosso as the Cachoerinha suite accompanied by the Serra de Providência rapakivi suite in Rondônia. Similar age rocks are found in the Baltic shield and include both calc-alkaline accretionary terranes and rapakivi within-plate suites. It is suggestive, perhaps permissible, to conclude that the Rio Negro-Juruena province and the Baltic shield were laterally connected during the late Paleoproterozoic.

Events between 1.51 Ga to 1.46 Ga at SW Amazonian craton is represented by the Rio Alegre arc comprised by mantle-derived origin rocks originated in ocean floor intruded by calcioalkaline magmatism. The Pinware terrane is a significant example of contemporaneous rocks in Labrador, although they are described as result of an extensional event. In Baltica there is a lack of orogenic rocks of this age.

Between 1.45 Ga to 1.42 Ga there is the Santa Helena batholith, which is a relatively rare example of juvenile crustal growth ca. 1500 to 1400 Ma. Also, ca. 1450 Ma "anorogenic" plutons within the Paleoproterozoic marginal belts of Laurentia orogenic belts of that age are relatively uncommon. There had been reported juvenile 1.50 to 1.45 Ga crust in the midcontinent region of the United States, and new evidences for a ca. 1450 juvenile terrane (Quebecia) within the Grenville province.

The San Ignacio orogeny is an important lateral accretion to the Amazonian Craton between 1.35 Ga to 1.32 Ga. It is reasonable to admit that coeval intermittent intraplate bimodal magmatism

(Alto Candeias intrusive suite) in Rondonia accompanied by sedimentation in rift-related settings (Palmeiral and Prosperança sediments) could be regarded as distal manifestation inboard of rifting environment related to the development of the San Ignacio orogeny. The lack of events between 1300-1250 Ma in the SW Amazonian Craton indicates the initial period of sedimentation referable to the Sunsás, Aguapeí, and Nova Brasilandia basin.

The Sunsás Arc has been considered as resulting of the inversion a passive continental margin (at about 1.2 Ga), encompassing deep marine turbiditic sediments that have experimented subduction under the overthrusting plate coined as San Pablo terrane (comprised of 1.92 Ga Correreca granitoids). Relevant units recorded in the Nova Brasilândia Terrane and linked to the rifting stage include mantle-derived tholeiitic sill, stocks, gabbro and diabase dykes, emplaced at 1150 Ma which attest a widespread juvenile magmatism. A U/Pb zircon age of a S-type granite at 1100 ± 15 Ma dates a metamorphic event of the mafic rocks, which are contemporaneous with turbidites melting (including Ar/Ar equivalent ages). Suture rocks of coeval age were found in the Arequipa-Antofala and may be correlated to the first Laurentia-Baltica-Amazonia collision of the Rodinia amalgamation.

Finally, there is ample evidence of ca. 1000-970 Ma orogenesis in Bolivia and Brazil. The deformation and metamorphism in Aguapei Group are probably inboard manifestations (fold and thrust belt) of the more intense continent-continent collision occurring to the west in Bolivia (Sunsas Orogeny). Important anorogenic magmatism is reported widespread SW Amazonian Craton during this period of time.

This review, based mainly on the available recent U/Pb, Sm/Nd geochronological data, chemical studies, constitutes a preliminary attempt to model the Proterozoic evolution of this sector of the Amazonian Craton also aiming to stimulate future research. Further on it is intended to search temporal correlations between the tectonic events in the southwestern Amazonian Craton, Laurentia and Baltica and thereby provide constraints for plate tectonic reconstruction. It is postulated that geologic evolution of SW Amazonian Craton suggests it was part of a Mesoproterozoic supercontinent, which existed from 1800 Ma to 1500 Ma.

LA-ICP-MS U-PB DATING OF DETRITAL ZIRCONS FROM SEDIMENTS OF THE SOUTHERN PART OF THE SIBERIAN CRATON: CONSTRAINTS FOR PRECAMBRIAN SUPERCONTINENTS

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Studies of detrital zircons from sediments which were accumulated in different settings (intra-plate, passive / active margins, foreland basins etc) provide important clues for understanding long supercontinenal cycles. Sedimentary successions of the southern part of the Siberian craton recorded various stages of the Precambrian supercontinents’ evolution and the history of the Paleoasian Ocean. Here we present first results of the LA-ICP-MS U-Pb datings of detrital zircons from Late Precambrian sedimentary rocks of Pre-Sayan and Cisbaikalia. U–Pb isotopic analyses were carried out by Laser Ablation ICP-MS at the Institut für Mineralogie, Westfälische Wilhelms-Universität Münster, Germany (for Cisbaikalia) and at Tianjin Institute of Geology and Mineral Resources (for Pre-Sayan).

One of the most spectacular Neoproterozoic sedimentary sections is exposed in the western Baikal region (Cisbaikalia) where they are represented (from the bottom) by Baikal Series (Goloustnaya, Uluntui and Kachergat suites) and Ushakovka suite. The upper part of this section is covered by Lower Cambrian deposits. Basal layers of the Baikal Series uncomfortably overlie the early Precambrian Siberian craton’s basement rocks. The age of the Baikal Series’ lower part is still under debate.

Within the Pre-Sayan area basement rocks (early Precambrian metamorphic and magmatic complexes) are overlain by Neoproterozoic Karagas Group interpreted to have been formed on a passive continental margin. This Group contains Shangulezh (lower), Tagul (middle) and Ipsid (upper) suites which are composed mainly by terrigenous and carbonate sediments. The lower and middle Karagas Group is intruded by 741 ± 4 Ma mafic sills and there is some field evidence of their emplacement into non-consolidated wet sediments. The age of sills provides a younger limit for the deposition of these sediments. The upper Karagas Group is intruded by 612 ± 6 Ma mafic dykes, indicating that Karagas Group has been deposited between ~740 and 612 Ma. The unconformably overlying Ediacaran Oselkovaya Group (Marna, Uda and Asinskaya suites) contains mainly clastic sediments with carbonates and turbidites in its upper part, although its precise age is debated. No intrusions are reported in the Oselkovaya Group. It allows us to consider this group to be younger than 612 Ma.

87 zircons from sandstones of each suite of the Baikal Series and of the Ushakovka suite were dated. The results demonstrate that the input of “non-Siberian” zircons which came from various terranes of the Paleoasian Ocean (microcontinents, island arcs etc.) gradually increases from older to younger suites of the Baikal Series, reflecting opening, development and closure of this paleobasin. Our results suggest the maximum upper age limit for the deposition of the Baikal Series as Early Ediacaran while the Ushakovka suite can be as young as Late Ediacaran.

More than 110 zircons from sandstones of each suite of the Karagas Group and of the Uda suite were dated. We found that all sediments of the Karagas Group contain typical “Siberian” (~3400; 3000; 2700; 2500; 1850; 1750 Ma) detrital zircons only. Numerous Late Precambrian (~1000 – 613 Ma) (1/3 from analyzed) detrital zircons were found in sandstone of the Uda suite, marking the maximum upper age limit for the deposition of this suite as Early Ediacaran.

Age distribution of Neoproterozoic detrital zircons in sandstones of Ushkovka and Uda suites reflects processes related to the breakup of Rodinia and to the history of the Paleoasian Ocean. Ediacaran zircons mark early stages of the oceanic closure and the formation of the Central Asian orogenic belt.

The absence of detrital zircons with ages between 1600 – 1000 Ma in both areas (Cisbaikalia and Pre-Sayan) confirms the hypothesis of Mesoproterozoic supergap in igneous activity within the southern part of the Siberian craton. This gap approximately coincides with the period between assembly of Nuna and breakup of Rodinia. We suggest that the absence of major geological activity during this interval might be explained by the position of southern Siberia within internal part of the ‘Transproterozoic supercontinent’ - a fragment of Nuna that did not disperse until the late Neoproterozoic breakup of Rodinia (Gladkochub et al., 2010). Paleomagnetic reconstructions confirm this hypothesis demonstrating that in both Precambrian supercontinents (since ~1.9 until ~0.7 Ga), the southern margin of Siberia had been located far from oceans - opposite to the northern Laurentia.

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PALEOMAGNETIC EVIDENCE FOR CRUSTAL SHORTENING DURING THE PALEOPROTEROZOIC

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In the last 200 million years, crustal shortening of several thousand kilometers has taken place across SE Asia as a result of the Himalayan and Mongol Okhotsk collision zones. Offset polar wander paths between the Slave and Superior Archean cratons in Canada for the time interval of 2.2 to 2.0 Ga can be explained by evoking crustal shortening of about 5000 km as a result of the intervening Trans Hudson and Thelon orogens. The results suggest that crustal shortening is an important component of continental collision which must be assessed in any re-assembly of Precambrian continents, and that the dimensions of Precambrian, and especially Archean shields, presently preserved is significantly different compared to the time before 2.2 Ga.

NAIN/GARDAR-AGED MAFIC DYKES AS A TEMPORAL AND MAGMATIC 'BRIDGE' ACROSS NORTH ATLANTIC CRATONIC BLOCKS: GEOCHRONOLOGIC, PALEOMAGNETIC AND GEOCHEMICAL EVIDENCE FROM LABRADOR AND SW GREENLAND

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The North Atlantic craton includes two principal Archean cratonic blocks, one in Labrador and the other in S Greenland, that rifted apart in the Mesozoic. Precise U-Pb ages are now available for many Proterozoic magmatic units on each block. In Labrador, most Nain Plutonic Suite (NPS) intrusions are cut by swarms of undeformed olivine diabase dykes, but in the Gardar province of SW Greenland, the oldest dykes predate most plutons. By comparing dyke swarm orientations, paleomagnetic poles and geochemical characteristics for these well-dated units, it is now possible to reconstruct several discrete widespread magmatic events, some of which occur on both cratonic blocks. Between ca. 1360-1290 Ma, dozens of large NPS granitoid and anorthosite plutons were emplaced, spanning an area over 20,000 km^2. During the late stages of NPS magmatism, coastal regions were intruded by thin (<5m), ca. 1290 Ma Nain diabase dykes, trending roughly N-S and characterized by titanaugite, high-P2O5 (HP), low mg#, high REE abundances and elevated La/Sm. Together with initial εNd compositions (-3 to -9.5), these transitional alkalic compositions suggest they are products of low-volume mantle melts with some lithospheric influence. They are synchronous with youngest, evolved, high-level alkaline and peralkaline NPS granites. Equivalents of these HP dykes have not been identified in SW Greenland. The largest swarm of Nain dykes, emplaced at ca. 1280 Ma, are thick ESE-trending, low-P2O5 (LP) diabases with olivine tholeiite to transitional compositions. LP dykes have more primitive mg#, and higher REE abundances and La/Sm than older HP dykes. Nain LP dykes have precise age correlation with ESE-trending BD0 Gardar dykes of SW Greenland. In a pre-Mesozoic reconstruction of the two cratonic blocks they form a continuous swarm, with similar geochemistry and paleopoles. At ca. 1272 Ma, a discrete set of NE-tending transitional to mildly alkalic "Harp" dykes were intruded in Labrador. Both ESE (LP) and NE (Harp) dykes likely reflect slightly larger volume mantle melts, and initial εNd compositions (+3 to -5) for each reveal magma sources in depleted mantle, locally modified by crustal contamination. Based on paleomagnetism and dyke trend, Harp dykes appear to extend into SW Greenland as "BD1-BD3" dykes, although precise dating is not yet available from Greenland to confirm this correlation. However, paleomagnetic data from many NE-trending dykes in both Labrador and SW Greenland suggests that many "Harp" and "BD1-BD3" dykes could be much younger than 1272 Ma, possibly emplaced in a younger, ca. 1180-1140 Ma interval of Gardar magmatism. Paleopoles from these "younger" NE dykes form a swath that overlaps the paleopole from the 1163 Ma Younger Giant Gabbro Dyke of Tugtutôq in SW Greenland and paleopoles from 1140-1110 Ma dykes and sills from elsewhere in Laurentia.

In summary, dyke emplacement across both regions appears to record a magmatic and temporal 'bridge' between the NPS and Gardar igneous provinces, now separated onto two crustal blocks following younger, limited rift and drift. Dyke activity may have coincided with (plume-related?) uplift and migration of increasingly alkaline NPS igneous activity to the SE, transitional directly to the Gardar province

THE NATURE, ORIGIN AND PRECISE U-Pb GEOCHRONOLOGY OF THE 1.63 Ga MELVILLE BUGT SWARM, GREENLAND: TESTABLE LINKS WITH THE 1.5-1.6 Ga BALTIC RAPAKIVI PROVINCE?

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Results are presented from an integrated U-Pb geochronological and paleomagnetic study of the Melville Bugt dyke swarm from western Greenland. The swarm comprises mostly trachybasalt dykes up to 200 m in width, with an average width of about 80 m, and extend for at least 1200 km in a NNW direction. The swarm appears to terminate in the north in the vicinity of Thule and towards the south to pass under Greenland's inland ice cap. The sense of a magnetic polarity change in the Melville Bugt dykes has been obtained from precise U-Pb dating of baddeleyite. 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, together with a comparison of paleomagnetic pole positions between Laurentia and Fennoscandia, allow the possibility that the 1.6 Ga Melville Bugt dyke swarm once trended towards the 1.5–1.6 Ga Fennoscandian rapakivi province, or its possible extension in Amazonia, raising the conjecture that the dyke swarm was fed laterally from this magmatic province. Satellite imagery from southeast Greenland shows several NNW-trending dykes that may represent a southerly continuation of the Melville Bugt swarm, necessary if the dykes are to have the rapakivi province as a source. The use of high precision U-Pb geochronology to establish the sense of paleomagnetic reversals promises to be a useful tool in continental reconstructions.

A PRECISE U-Pb AGE FOR THE GREAT WHIN DOLERITE COMPLEX, NE ENGLAND: DATING THE EUROPEAN PERMO-CARBONIFEROUS LIP AND RIFT EVENT IN THE PANGEAN SUPERCONTINENT

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The Whin Sill is one of the largest hypabyssal igneous intrusions in Britain and represents an important time marker in the regional stratigraphy of NE England. More correctly referred to as the Whin Sill complex, it comprises a series of sills of varying thickness and a suite of late dykes. The main intrusion is a quartz-dolerite known as the Great Whin Dolerite Complex (GWDC), with individual sills reaching 90 metres in thickness. Its widespread and transgressive nature, combined with several discrete intrusive phases make it a valuable regional time marker for a variety of geological events. A singular olivine-bearing sheet known as the Little Whin Sill is interpreted to be an early differentiate of Whin magma. The saucer-shaped GWDC crops out in an arcuate pattern, underlying an area of ~5000 km^2, with a volume estimated at >200 km3, not including its probable extension beneath the North Sea. Sheets of Great Whin dolerite are restricted to Carboniferous sedimentary rocks, from stratigraphic levels at least as old as Asbian, up through late Westphalian Coal Measures. Eroded clasts of Whin dolerite have been recognized in Lower Permian-aged continental breccias. The growing importance of the sill complex in regional European studies of Permo-Carboniferous magmatism and tectonics highlights the need for a refined, accurate and precise age for the intrusion. In this study, we have focused on the Hadrian's Wall-Pennines Sill, characterized by 0.5-1 mm grain size, subophitic textures (dominantly labradorite + augite), lesser pigeonite, titanomagnetite, apatite, K-feldspar and quartz. At High Force quarry in Teesdale, the 70m+ thick GWDC intrudes Brigantian Tyne Bottom Limestone. Here, lenses of diffuse, concordant gabbroic pegmatite in the sill carry relatively abundant baddeleyite. A weighted average $^{206}Pb/^{238}U$ age for four concordant and nearly concordant multigrain fractions of baddeleyite is 297.4 ± 0.4 Ma (2σ). This result is an order of magnitude more precise than previous age determinations for emplacement and crystallization of the GWDC, and represents one of the more reliable dates for European Permo-Carboniferous LIP magmatism. Combined with field relations this new age places a robust minimum constraint on the absolute age of the Permo-Carboniferous stratigraphic boundary in the UK. The magnetic polarity of the GWDC is in accord with intrusion during the Kiaman reversed superchron and provides firm geochronological support for establishment of this long-lived reversal before 297 Ma. The new U-Pb age for the GWDC strengthens correlation with nearby Midland Valley sills of Scotland, the main (older) phase of alkaline magmatism in the Oslo Rift, and possibly the early phase of Scania dykes of S Sweden. This tripartite association, with short period of emplacement and large volumes of magmatism, supports the hypothesis that they represent components of a giant radiating system focused on a North Sea mantle plume (e.g. “Jutland event”). In this scenario, the GWDC would represent a sill complex fed distally from a central plume source some 500 km to the east.

THE JURASSIC MAFIC AND ULTRAMAFIC DIKES OF ANTARCTICA: IMPLICATIONS FOR GONDWANA BREAK-UP PROCESS AND MANTLE SOURCES OF KAROO CONTINENTAL FLOOD BASALTS

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The Karoo continental flood basalt province was emplaced across the land masses of southern Africa and western Dronning Maud Land, Antarctica, when they still were part of the Gondwana supercontinent (Fig. 1). Voluminous (~2 000 000 km^3) magmatic activity at ~180 Ma ago was followed by the opening of the Indian Ocean at ~170–160 Ma ago. The widespread flood basalts of the African Karoo have been extensively studied (e.g., Erlank, 1984), but their origin has remained a matter of debate. This stems from the fact that even the most primitive magma types from African Karoo show geochemical evidence of a significant lithospheric component.

Our recent studies in the Antarctic Karoo (Fig. 1) have revealed three magma types that represent uncontaminated highly magnesian melts formed deep in the mantle (Riley et al., 2005; Heinonen et al., 2010; Heinonen, 2011). These rocks provide key information on the Karoo flood basalt magmatism: **1) The depleted ferropicrites of Vestfjella** are coeval with the Karoo main pulse (~180 Ma) and have Sr, Nd, Pb, and Os isotopic signatures that are compatible with a depleted upper mantle source. Based on geochemical modeling, this source may also have produced the parental magmas for most of the contaminated flood basalts of Vestfjella. **2) The depleted picrites of Ahlmannryggen** show similar Nd and Os isotope compositions with the Vestfjella depleted ferropicrites, but exhibit more enriched Sr and Pb isotopic compositions and relative enrichment of high-field strength elements (e.g., TiO_2 > 3 wt. %) suggestive of a distinctive depleted mantle source. **3) The enriched ferropicrites of Vestfjella** that show OIB-like trace element and Sr, Nd, Pb, and Os isotopic characteristics likely sampled subordinate mantle heterogeneities, such as recycled oceanic crust or melt-metasomatized portions of the sublithospheric or lithospheric mantle.

The highly magnesian depleted ferropicrites of Vestfjella represent the hottest and most primitive magma type described from the Karoo province. Their geochemical compositions, however, are entirely compatible with a predominant depleted upper mantle source and do not require deep mantle plume components. Overall, our data for uncontaminated magma types and our geochemical modeling of voluminous flood basalts lend support to generation of Karoo magmas mainly as a consequence of heating of the upper mantle beneath the Gondwana supercontinent. The role of enriched (plume/recycled?) sources remains to be constrained.

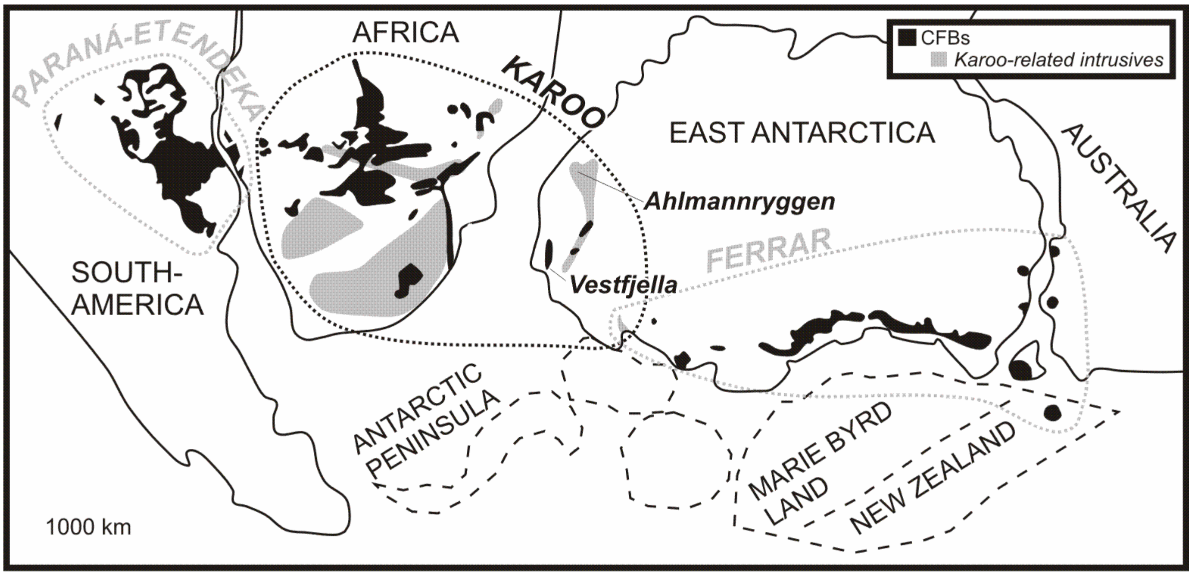

Figure 1. Distribution of Mesozoic CFBs in reconstructed Gondwana supercontinent. In the case of the Karoo province, the known extent of intrusive equivalents (found outside CFBs) is also shown. See Heinonen (2011) for references.

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MECHANISM OF SUPERCONTINENT COLUMBIA FRAGMENTATION

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The 1.3~1.2 Ga fan-shaped Mackenzie dyke swarm and other similar- aged dyke swarms in the Canadian Shield constitute the subswarms of a Late Mesoproterozoic giant radiating swarm. The Late Mesoproterozoic mafic dyke swarms in Australia and East Antarctica might constitute additional subswarms of the giant radiating dyke swarm. A possible Late Mesoproterozoic mantle plume is placed at the focal area of the giant radiating dyke swarm between North America and the landmass (West Australia– East Antarctica). This mantle plume triggered the continuous extension at ca. 1.3–1.2 Ga, which extended into much of supercontinent Columbia and led to the final fragmentation of the supercontinent.

The giant fan-shape Mackenzie dyke swarm is the largest dyke swarm in the world, which extend 2100 km long and 1800 km wide area. The mechanism of the giant dyke swarm will help us to insight the geodynamics of the fragmentation of supercontinent.

The 1.27 Ga stress field on the Canadian Shield calculated by the ‘‘Plug’’ model (Hou et al., 2010) explains the radiating nature of the Mackenzie dyke swarm around the Coppermine River lava field by local stress concentrations.

The parallel nature of the dyke swarm at distance (more than 1000 km) from the focal source can be explained by the existence of a regional tectonic stress field created by ridge push acting on the southeast margin of the Canadian Shield from the Grenville Ocean. The thin elastic plate and two-dimensional cross-section modeling suggest that the interaction between stresses from a mantle plume upwelling and the Grenville Ocean spreading play an important role in the intrusion mechanism of the Mackenzie dyke swarm. The change in dyke orientation from N-S trending to NW-SE trending is caused by coupling between resistance from the focal area (Plug area) and a Grenville Ocean ridge push.

The mechanics modeling of giant radiating Mackenzie dyke swarms tell us that the giant radiating dyke swarms trigger the initial breakup of supercontinent and led to the final fragmentation of supercontinent, which are part of LIPs related to mantle plume.

AGE AND Sm-Nd ISOTOPES OF PALAEOPROTEROZOIC MAFIC ROCKS IN FINLAND – RIFTING STAGES OF ARCHAEAN LITHOSPHERE AND MULTIPLE MANTLE SOURCES

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Isotopic studies on mafic dykes, intrusions and volcanic rocks in Finland have revealed rifting of the Archaean lithosphere at several distinct stages including ca. 2.44 Ga, 2.3 Ga, 2.22 Ga, 2.15 - 2.11 Ga, 2.05 Ga, 2.0 Ga, 1.95 Ga and 1.8 Ga (Huhma et al 2011 and references therein). Much of the relevant age data have been published in the special volume containing U-Pb data on more than 180 samples from Finnish Lapland (Vaasjoki, 2001, editor). Many of these results date gabbroic rocks from larger intrusions and dykes, and can also be used to reliably constrain the ages of volcanic events, which have produced the major mafic formations especially in Central Lapland. Mafic rock associations in the Karelian domain provide time-integrated probes either from the lithospheric mantle below the Archean craton, asthenospheric depleted mantle or mantle plumes from deeper sources. Some mafic rocks may be regarded as representing ancient Large Igneous Provinces.

Samarium-neodymium mineral and whole-rock analyses have been made at GTK since the early 1980's. The database currently includes more than 500 analyses on ~ 70 Palaeoproterozoic mafic rock units in the Karelian domain. The emphasis has been on most pristine samples available and generally the Sm-Nd mineral ages on such relatively well-preserved samples are consistent with the available U-Pb zircon ages. As many of the initial ε_{Nd} values are based on the Sm-Nd mineral isochrons, they should give reliable estimates for the initial isotopic composition of the rocks in question. These data together with U-Pb ages and geochemical and other geological information provide tools for constraining the age and origin of the magmas of the major mafic episodes and thereby the evolution of lithosphere and mantle components.

The initial ε_{Nd} values range from very positive to strongly negative (Figure 1). High initial values suggest derivation from depleted mantle sources, whereas low values point to a large contribution from old enriched continental lithosphere. Crustal contamination of ultramafic magma at depth may explain many features observed in such rocks as e.g. the 2.44 Ga layered mafic-ultramafic intrusions with ε_{Nd} of –2, but the isotopic results also show that various mantle sources with distinct isotopic compositions must have existed during the Palaeoproterozoic. Evidence of this is provided by high-REE mantle-derived rocks showing a range of initial ε_{Nd} values from nearly chondritic (e.g., the 2.61 Ga Siilinjärvi carbonatite, 1.95 Ga Jormua OIB, 1.78 Ga lamprophyres) to highly positive (e.g., the ca. 2.0 Ga Laivajoki and Kortejärvi carbonatites).

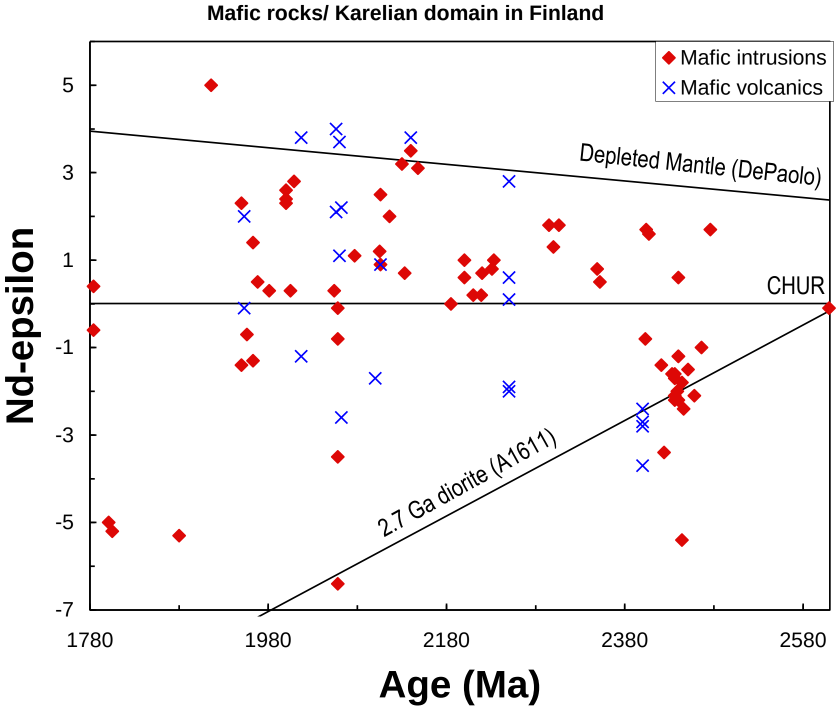

Figure 1. Nd-epsilon vs. age diagram for Palaeoproterozoic mafic rocks from the Karelian domain in Finland. The evolution lines for bulk earth (CHUR), model depleted mantle and typical Neoarchaean granitoid (A1611) are shown for reference. The ages of most intrusions are well constrained by U-Pb zircon method, the age of many volcanic rocks is estimated from geological context.

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FROM RODINIA TO GONDWANA WITH THE 'SAMBA' MODEL – A DISTANT VIEW FROM BALTICA TOWARDS AMAZONIA AND BEYOND

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In a recently published model, Johansson (2009) proposed on geological grounds that Baltica, Amazonia and West Africa formed a single coherent landmass from at least 1800 Ma to at least 800 Ma, and perhaps until 600 Ma, with the (present-day) northwest side of Amazonia attached to the southwest side of Baltica (along the Transeuropean suture zone), and the west coast of West Africa attached to the southern (Black Sea – Caspian Sea) margin of Baltica. In such a configuration, referred to as the 'SAMBA' (South America – Baltica) model, the geology of the three now dispersed cratons forms a coherent pattern, with Archean nuclei surrounded by early Palaeoproterozoic (2.0 – 2.2 Ga) orogenic belts in the 'east', and successively younger orogenic belts that can be followed from Baltica to Amazonia in the 'west'. As parts of the late Palaeoproterozoic to Mesoproterozoic supercontinent, SE Laurentia, SW Baltica and SW Amazonia formed a curved active margin facing an open ocean from 1900 Ma to 1250 Ma. From c. 1250 Ma to 1000 Ma, Baltica, together with Amazonia and West Africa, rotated c. 75º clockwise relative to Laurentia, and collided with the present-day southeast margin of Laurentia forming the Grenville, Sveconorwegian and Sunsas orogens, as suggested by numerous others, as part of the process leading to the formation of Rodinia.

In the 'SAMBA' model, Baltica and Amazonia occupy a similar position along the Grenville margin of Laurentia as in the Rodinia reconstruction of Li et al. (2008), with Baltica close to Labrador, albeit with Amazonia in a different orientation and lacking any suture with Baltica. In such a configuration, the present-day Andean margin of South America, together with Baltica, could have formed the conjugate margin to the Grenville margin of Laurentia, with the Arequipa-Antofalla Block (Loewy et al. 2004) filling the gap between the central Grenville belt of Laurentia and the Sunsas belt of Amazonia, and the Argentine Precordillera (Dalziel 1997, Thomas & Astini 2003) filling in the Ouachita embayment.

Whether the more easterly parts of South America, e.g. the Rio de la Plata and Sao Francisco cratons, and the Congo and Kalahari cratons in Africa were part of Rodinia or not, and what their positions and orientations might have been if being parts of Rodinia, has been a controversial issue (cf. Cordani et al. 2003, Kröner & Cordani 2003, Fuck et al. 2008, Loewy et al. 2011). It is here proposed that these cratons were placed close to SW Laurentia and E Antarctica, with E Antarctica, Australia and India in a 'SWEAT'-like configuration with respect to Laurentia (cf. Moores 1991). In such a configuration, the present-day southern African and eastern South American cratons would have been part of Rodinia, but still separated from Amazonia and West Africa by a wide 'Brasiliano' ocean embayment. The change from a Rodinia to a Gondwana configuration would involve rifting of

Australia, E Antarctica and Kalahari from western Laurentia at c. 750 Ma, followed by c. 90º to 120º counterclockwise rotation of these cratons (+ India, Congo-Sao Francisco, and perhaps also Rio de la Plata) relative to Laurentia around a pole centered close to the Laurentia-Kalahari junction, leading to collision with Amazonia and West Africa at c. 600 to 550 Ma (cf. Hoffman 1991, Unrug 1997). This rotation closed the Brasiliano ocean, and opened and closed the Adamastor and Mozambique oceans, creating the various Brasiliano and Pan-African orogenic belts. At the same time, Laurentia and Baltica separated from Amazonia and West Africa and became independent continents. The rotation described above would correspond to a translation of the East Gondwana cratons with an order of magnitude of 15 000 km (3/8 of the circumference of the Earth) in c. 200 million years, corresponding to c. 7.5 cm/year. The highest speed, and the most prominent formation of juvenile crust, would occur in the largely oceanic Sahara – Nubia – Arabia sector of the Pan-African orogen. Rather than being an example of 'introversion' or 'extroversion', the change from Rodinia to Gondwana in this model would be more like the 90º 'orthoversion' model proposed by Mitchell et al. (2012).

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TERMINATION OF THE PALEOPROTEROZOIC CARBON ISOTOPE EXCURSION: EVIDENCE FROM THE NORTHERN FENNOSCANDIAN SHIELD

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The isotopic composition of Paleoproterozoic sedimentary carbonates provide evidence for a major perturbation in the carbon cycle, affecting the surface environments at 2.2 – 2.1 Ga. During that interval, the $\delta^{13}C$ values of dissolved inorganic carbon in the oceans increased to 10 ‰ and even higher (Karhu and Holland 1996). Carbon isotope records from different sedimentary successions indicate that the excursion was global in character. The positive excursion implies a major increase in the fractional burial rate of organic carbon, and it appears to have been one step in the irreversible oxidation of the atmosphere, oceans and the surface environments between 2.4 and 2.0 Ga. The beginning of the carbon isotope excursion is still poorly constrained to 2.3 – 2.2 Ga, but the termination of the event is relatively well defined to between 2115±6 and 2062±2 Ma.

The Peräpohja Belt in northern Finland is one of the key areas for studying the termination of the excursion. The succession comprises several carbonate sequences deposited in a tidal flat environment, and the whole succession represents a decline in $\delta^{13}C$ values from about +10 to +3‰. The Hirsimaa Formation is a pyroclastic unit between two dolostone units. A new U-Pb date of 2106±8 Ma from the Hirsimaa Formation gives a more accurate estimate for the time, when the oceans were returning back to the normal $\delta^{13}C$ values of about 0 ‰. In addition to the generally declining trend, the carbon isotope records from Peräpohja provide evidence for cyclically fluctuating $\delta^{13}C$ values at around 2106 Ma. The period of fluctuating $\delta^{13}C$ values ended in a distinct minimum in $\delta^{13}C$ between 2050 and 1970 Ma, indicated by new and published data from other stratigraphic sections in northern Fennoscandia.

The general form of the Paleoproterozoic carbon isotope curve appears to be different from that of the Neoproterozoic record. The Neoproterozoic $\delta^{13}C$ curve is presented by long-lasting periods of positive $\delta^{13}C$ values punctuated by sharp negative minima, often associated with glacial intervals. In contrast, the Paleoproterozoic $\delta^{13}C$ record is characterized by a single positive major excursion, lasting for 100 Ma or more, and apparently postdating the Paleoproterozoic glacial events. In the Fennoscandian Shield, the drop in the $\delta^{13}C$ values and the termination of the excursion appears to roughly coincide with the breakup of the Archean craton, possibly connected to the breakup of the Kenorland supercontinent.

The distinct minimum following the Paleoproterozoic carbon isotope excursion could be interpreted to mark a transition from voluminous organic carbon burial to a period with a minimal fraction of organic carbon in sedimentary carbon burial. An alternative explanation is related to a change in the atmospheric composition. Many lines of evidence indicate that the composition of the atmosphere changed from anoxic to oxic between 2.4 and 2.0 Ga. A minimum following the positive excursion in the $\delta^{13}C$ curve could be related to massive oxidative decomposition of sedimentary organic matter, increasing the proportion of biogenic, ^{13}C-depleted carbon in the marine dissolved carbonate reservoir (Kump et al., 2011).

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THE ROLE OF THE WYOMING CRATON IN PALEOPROTEROZOIC SUPERCONTINENTS OR SUPERCRATONS: NEW PALEOMAGNETIC AND GEOCHRONOLOGIC DATA FROM MULTIPLE DYKE SWARMS

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Various alternative models link the Wyoming craton to other Neoarchean/Paleoproterozoic blocks, such as Superior, Slave, and Kaapvaal; but quantitative constraints have been lacking. Wyoming contains numerous generations of dyke swarms confined to Precambrian basement uplifts, which permits integrated geochronologic and paleomagnetic studies to test the proposed ancient connections.

We here present our first results from this region with geochronologic and paleomagnetic data from two different dyke swarms dated at ca. 2160 and 1900 Ma. The Powder River swarm (ca. 2160 Ma) is a large mafic dyke swarm that is dated in multiple uplifts and contains a large differentiated dyke that also possibly spans multiple uplifts (the Bighorn Mountains and Wind River Range). Paleomagnetic results from 14 Powder River dykes, integrated with clockwise-corrected data of Harlan et al. {, 2003 #189}, support a viable reconstruction at ca. 2160 Ma of southeastern Wyoming directly adjacent to southern Superior. Our paleomagnetic reconstruction closely resembles that proposed by Roscoe and Card {, 1993 #561}, which aligned the Snowy Pass Supergroup of Wyoming as a conjugate rift margin mirroring the Huronian Supergroup of southern Superior. However, our reconstruction should be tested by additional results from older generations of dykes, to determine whether a long-lived 2.7-2.1 Ga connection is viable.

The Sourdough swarm (ca. 1900 Ma) is dated from the Bighorn Mountains, but may also include dykes from the Beartooth Mountains with similar trends. Paleomagnetic results from 9 dykes, supported with a positive baked-contact test, are distinctly different from the Molson dyke paleomagnetic pole (ca. 1880 Ma) both in present coordinates and in the Roscoe and Card {, 1993 #561} fit. The Sourdough pole is also distinct from the Clearwater Anorthosite pole (ca. 1915 Ma) and various poles from the Slave craton (ca. 1890-1870 Ma), in present Laurentian coordinates. These results suggest that by 1900 Ma Wyoming may have completed rifting away from Superior, but had not yet assembled into the western Laurentian terrane collage.

Other paleomagnetic results from many other dykes with different trends from different uplifts have yet to be paired directly with a precise age. Results from the Kennedy swarm (2010 Ma; Cox et al.{, #95}, 2000) in the Laramie Mountains and other swarms in the Granite, Ferris, and Seminoe Mountains (2200-1900 Ma?) will likely refine the rifting history of putative supercraton Superia, leading to Wyoming's independent motion before the assembly of Laurentia. Additional dykes from the Beartooth and Bighorn Mountains that are crosscut by these younger swarms are likely in the age range 2600-2200 Ma. These older swarms could provide a valuable test of the Roscoe and Card {, 1993 #561} fit from the time when Wyoming may have been part of supercraton Superia, and also provide possible connections to fragments that rifted away from Superia earlier than Wyoming. Finally, owing to the existence of multiple dated mafic intrustions of approximately 2700 Ma, including the Stillwater complex {Wall, 2010 #612} and a dyke from the Owl Creek Mountains {Frost, 2006 #157}, a set of new paleomagnetic data may provide future paleomagnetic poles for the Neoarchean, affording a new suite of paleomagnetic data to be compared to poles from the Kaapvaal, Superior, Tanzania, and Zimbabwe cratons.

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PALEOMAGNETIC STUDY OF SATAKUNTA SANDSTONE, SW-FINLAND: IMPLICATIONS FOR BALTICA DURING THE PROTEROZOIC

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A paleomagnetic study of the Proterozoic Satakunta sandstone, SW Finland, was done to obtain a new paleomagnetic pole for Baltica and to verify the union of Baltica and Laurentia between 1.83 to 1.26 Ga (Pesonen *et al.* 2003). The sandstone was deposited in a graben, formed by rifting 1.65 Ga ago, and later intruded by post-jotnian diabase (1.26 Ga). The age of the upper part of the sandstone is estimated to be ca. 1.3 - 1.4 Ga old (Kohonen & Rämö 2005).

A previous paleomagnetic study on Satakunta sandstone by Neuvonen (1973) yielded a mean direction of D_m = 24; I_m = -41 which is close to the post-jotnian diabase direction of D_m = 35.5; I_m =-34 and led us to question the primary origin of the sandstone direction.

Petrophysical, paleomagnetic and rock magnetic measurements were carried out on sandstone and diabase samples from Satakunta at the Solid Earth Geophysics Laboratory at the University of Helsinki. Stepwise AF and thermal demagnetization was performed on the samples and NRM measurements were carried out with a 2G SQUID magnetometer. Magnetic hysteresis and thermomagnetic measurements were done on selected samples using a VSM and KLY-3 kappabridge respectively.

The AF and thermal treatments coupled with hysteresis and thermomagnetic data suggest that the ChRM of the sandstone is carried by PSD and/or MD magnetite and hematite. In addition to PEF, two prevailing components were identified in the sandstone: a NE (SW) magnetic direction with a shallow inclination, and a NE direction with a moderately steep upward inclination (Figure 1 A). The latter is very similar to the ChRM of the diabase samples, and is therefore considered to be a secondary component created by baking from diabase intrusion at 1.26 Ga.

The occurrence of dual polarities and a positive tilt correction confirm the primary origin of the shallow component in the sandstone. A mean site direction (after tilt correction) was calculated at D_m = 25.7, I_m = 2.8 (N = 37, α_{95} = 6.8, k = 38), which yielded a paleomagnetic pole located at 27.1°N, 172.9°E (A_{95} = 4.8). This implies that Satakunta sandstone was deposited earlier at *ca.* 1.6 Ga (Figure 1 B). Using the new paleomagnetic pole, a reconstruction of Baltica and Laurentia at 1.6 Ga will be presented at the symposium.

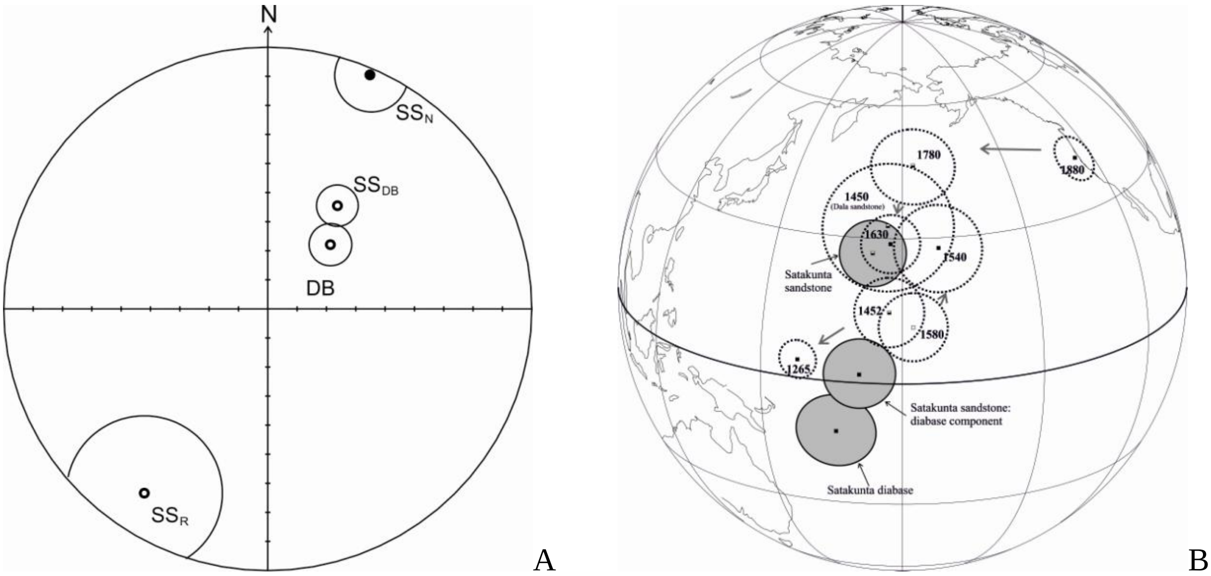

Figure 1. A) Mean directions of Satakunta sandstone and diabase: SS_N = sandstone normal polarity, SS_R = sandstone reversed polarity, SS_{DB} = sandstone secondary (diabase) component, and DB = diabase. B) Paleomagnetic poles of sandstone and diabase with 95% confidence circle plotted among paleomagnetic key poles (Buchan *et al.* 2000) and other relevant Proterozoic poles (Lubnina *et al.* 2010, Pisarevsky & Bylund 2010).

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PALEOMAGNETIZATIONS IN CENTRAL FINLAND: KEURUU DYKE SWARM AND SHATTER CONES FROM KEURUSSELKÄ METEORITE IMPACT STRUCTURE

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The studied area (62°08' N, 24°37' E), which include Keuruu diabase dyke swarm and Keurusselkä meteorite impact structure, is situated within the Central Finland Granitoid Complex (CFGC) (Nironen 2003). CFGC was formed 1890–1860 Ma ago during the peak phase of the Svecofennian orogeny, where the growing Svecofennian island arc system collided against the Archaean continent. Continental deformation, metamorphism and crust forming magmatism occurred at approximately 1900–1800 Ma. The granitoids with biotite, hornblende, titanite, apatite, magnetite, and zircon (Kähkönen 2005) are predominant rocks in the CFGC together with schists and gneisses. Keuruu diabase dyke swarm cut these rocks in several locations. Arc-type volcanic rocks, which are metamorphosed at high-T and low-P amphibolite facies, also characterize this part of the Paleoproterozoic crust. U-Pb (Zr) ages of the granitoids in the Keuruu region show crystallization age of 1886 to 1880 Ma (Geological Survey of Finland database). Volcanic rocks in CFGC are somewhat older, approximately 1900 Ma.

The Keuruu diabase dyke swarm carries a characteristic Svecofennian component with normal and reversed polaritites. The carriers for the remanent magnetization were observed to be magnetite (this study; Puranen et al. 1991). The isolated remanent magnetization direction yields the Svecofennian pole. This pole is consistent with the Svecofennian key poles presented in Buchan et al. (2000) and implies that the diabase dykes were crystallized simultaneously with the Paleoproterozoic crust.

The Keurusselkä impact structure, discovered in 2004, is a deeply eroded complex crater that yields in situ shatter cones with evidence of shock metamorphism, e.g., planar deformation features in quartz (Ferriere et al 2010). The suggested central uplift with shatter cones is characterized by increased magnetization and susceptibility (Raiskila et al. 2011). Two main remanent magnetization directions carried by magnetite and pyrrhotite were isolated: (1) a characteristic Svecofennian target rock component A and (2) component B, which is obtained from shatter cones and its pole corresponds with the 1120 Ma pole of Salla diabase dyke (Salminen et al. 2009) It is also in agreement with the Argon-age of 1140 Ma from a pseudotachylitic breccia vein in the central part of the structure (Schmieder et al. 2009). Therefore, component B could be related to the impact, and thus represent the impact age.

Keurusselkä and Salla poles create a large clockwise loop in the Precambrian APWP of Baltica from 1265 Ma to 1036 Ma, Salla pole (1122 Ma) being the apex of the loop. The resemblance between the pre-Sveconorwegian (approximately 1.3–1.0 Ga) APWP loops of Baltica, Laurentia (including Logan Loop), and Kalahari-Grunehogna are discussed in Salminen et al. (2009), although these cratons seem to reach their apexes at different times. Thus, it is evident that the APWPs of Baltica, Laurentia, and Kalahari express similar loops, suggesting that they may share a analogous history. A likely explanation for the observed large loops is the proposed true polar wander (Evans 2003) at the late Mesoproterozoic, which provide hints that the proposed Mesoproterozoic Baltica–Laurentia unity in the Columbia (Hudsonland, Nuna) supercontinent assembly may have lasted until 1.12 Ga.

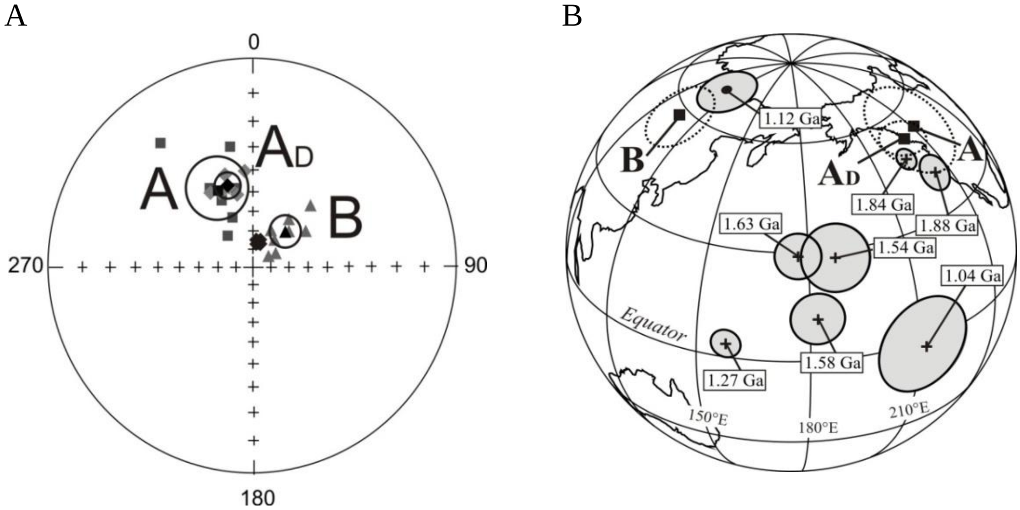

Figure 1. A) Mean paleomagnetic direction for characteristic Svecofennian component of Keuruu diabase dykes A_D and host rock A, and component B calculated from Keurusselkä meteorite impact. B) Mean paleomagnetic poles for components A_D, A and B with Baltica ‘‘key poles’’ and chosen well-dated poles, marked with A95 circles (Buchan et al. 2000; Salminen et al. 2009).

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PLATE MOTIONS RELATIVE TO THE GLOBAL HOTSPOTS FOR THE PAST 48 MILLION YEARS

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Hotspots are volcanic anomalies, either in an intraplate setting or in the form of excessive volcanism along the plate boundaries, not explained by classic plate tectonics. In the early 70's, along with a deep mantle origin, hotspots were proposed to move so slowly relative to one another such that they could be used as a reference frame fixed in the deep mantle for describing plate motions in an "absolute" sense (Morgan, 1971). Ever since the idea was first introduced, however, the rates of relative hotspot motion, and thus the limits of the hotspot frame of reference, have remained a source of heated debate with suggestions ranging from apparent fixity to rapid motion between the hotspots (e.g., up to 80 mm a^{-1} by Raymond et al., 2000).

The question of inter-hotspot motion is closely related to the estimation of true polar wander—rotation of the whole solid earth relative to the spin axis. A fundamental problem of global tectonics and paleomagnetism is determining which part of apparent polar wander—the apparent movement of age-progressive paleomagnetic poles relative to the continent in question—is due to plate motion, and which part is due to true polar wander. One approach for separating these is available if the hotspots are indeed tracking the motion of the mantle beneath the asthenosphere and are moving slowly relative to one another. In this case, a model of plate motion relative to the hotspots can be used to predict the positions of past paleomagnetic poles relative to the spin axis and thus estimate the amount of true polar wander.

Cumulative improvements in the age progression along the hotspot tracks, the geomagnetic reversal time scale, and relative plate reconstructions lead to significant changes in earlier results. In this study, we build on a new method for objectively estimating plate-hotspot rotations and their uncertainties (Andrews et al., 2006), and on our recent results that have demonstrated no significant motion between the Pacific and Indo-Atlantic hotspots since 48 Ma, and present a globally self-consistent model of plate motions relative to the hotspots for the past 48 million years. To obtain the model, we use the tracks of the Hawaiian, Louisville, Tristan da Cunha, Réunion and Iceland hotspots. All the hotspot tracks used in this analysis are among the most widely accepted candidates for a deep mantle origin. The poles of rotation are estimated for ages corresponding to some key magnetic anomalies used in plate reconstructions.

The new set of plate reconstructions presented here provide a firm basis for estimating absolute plate motions for the past 48 million years and, in particular, can be used to separate paleomagnetically determined apparent polar wander into the part due to plate motion and the part due to true polar wander.

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NORTH EUROPEAN TRANSECT (NET) – GROWTH OF NORTHERN EUROPE IN SUPERCONTINENT CYCLES

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Continents grow around stable nuclei in supercontinent cycles. The nuclei grow outward during collisional and accretional orogenies associated with the supercontinent formation. But also during the break up minor amounts of material is added to the rifted margins of the dispersed pieces of the supercontinent.

North European Transect (***NET***) – a compilation of three deep seismic reflection datasets ***BABEL*** (1600 km), ***FIRE 4-4A*** (580 km) and ***1-AR*** (1440 km) – transects the Baltic and Bothnian Seas, Northern Finland and Kola Peninsula, Barents Sea and ends at Franz Joseph Land. The profile covers the transition from Phanerozoic Central Europe to Precambrian Northern Europe and back to the Phanerozoic Barents Sea shelf. The profile images the growth of Northern Europe around Baltica in three supercontinental formation and break up cycles: Nuna, Rodinia and Pangea. With the help of seismic sections and paleomagnetic reconstructions we will show how Northern Europe grew to its present continental geometry.

The early stages of Nuna formation was characterized by the oblique convergence of Baltica and Laurentia (Mertanen and Pesonen, 2012) in the present northern part of Baltica, resulting in series of short lived orogenies or collisional phases (Lapland-Savo, Lapland-Kola, Svecofennian; Korja et al., 2006) at 1.9-1.85 Ga (***BABEL1*** *and* ***4&3and FIRE4*****;** Korja and Heikkinen, 2005). Simultaneous convergence of another continent in the South initiated arc formation south/southwest of Baltica. Based on paleomagnetic data this continent may have been North China, along with Amazonia that was in close connection with the growing Nuna supercontinent. The convergence and final collision of North China and Baltica around 1.85 Ga resulted in Svecobaltic orogen ***(BABEL B).*** After North China craton drifted apart from Baltica, a long lived, subduction margin (1.78 - TIB) was established at the western and southern margin of the Baltica-Laurasia (***BABEL B***). The long term (1.63-1.53 Ga) convergence of Amazonia and Baltica was finalized by docking of the continents in Gothnian orogeny (***BABEL A***). This finalized the compilation of Nuna supercontinent.

Although the dispersal of Nuna had begun in the inland areas with the formation of failed rift zones (Baltic Sea basin***, BABEL 1,C,B)***, a rifted Baltica margin was formed in the South after 1.2 Ga. The margin evolved into Songfreid-Törnqvist Zone (STZ) characterized by subvertical shear zones (***BABEL A***). Recent paleomagnetic data (Salminen et al., 2009) implies that in the North the departure of Laurentia from Baltica took place at about 1.12 Ga. After that the continents were separated.

During the compilation of the next supercontinent Rodinia, Baltica converged with Amazonia along STZ and grew outward with Sveconorwegian (1.0-0.9 Ga) terranes ***(BABEL A).*** The dispersal of Rodinia after ca. 600 Ma led to the opening of Tornquist Sea in the South and concurrently the Iapetus Ocean was opened in the West. The Tornquist Sea and Iapetus Ocean were closed at ca. 490-390 Ma when Avalonia and Laurentia collided obliquely with Baltica, resulting to the Variscian and Caledonian orogenic belts, respectively. The subvertical Trans-European Suture Zone ***(BABEL A)*** was formed in these early stages of Pangea assembly.

As part of Rodinia supercontinent formation, Baltica collided with Barentia resulting in Timanide orogeny, in the northeast (***1AR***). During the break-up of Rodinia an aborted rift was formed within Barentsia. Later peripheral tectonic events modified the interior parts of the Barentsia.

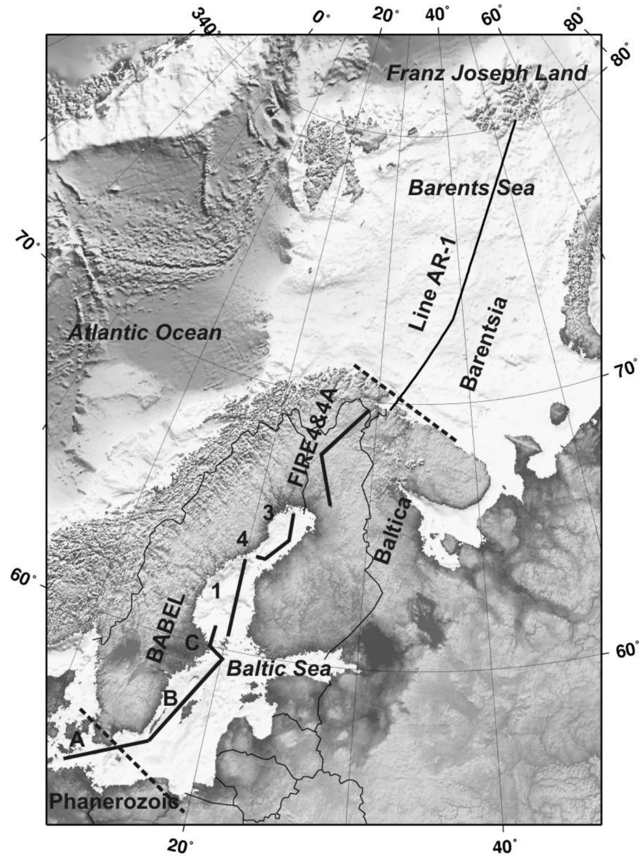

Figure 1. North European Transect - (NET)

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NEW AGE CONSTRAINTS FOR THE PALEOPROTEROZOIC FELSIC VOLCANIC ROCKS ASSOCIATED WITH THE KOILLISMAA INTRUSION, FINLAND

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The Archean–Proterozoic transition at ca. 2.5–2.4 Ga was marked by worldwide anorogenic bimodal magmatism that possibly reflects breakup of a late Archean supercontinent. The Koillismaa intrusion in northern Finland (Alapieti, 1982; Karinen, 2010) is a part of the ca. 2.44 Ga old layered intrusion suite in the Fennoscandian shield (Alapieti et al., 1990). The mafic layered complex in Koillismaa is associated with felsic plutonic and volcanic rocks that together form a complete bimodal magmatic suite (Lauri, 2004; Lauri et al., 2006). Alapieti (1982) published a zircon U–Pb TIMS age of 2436±5 Ma for the Koillismaa complex. The bulk age result included one zircon fraction from the granophyric rhyodacite that forms the roof of the intrusion. The fraction was very discordant, but plotted within the reference line defined by the mafic samples, suggesting that volcanic rocks were part of the magmatic system.

To confirm the age of the felsic volcanic rocks in Koillismaa a new sample (A2048 Suosaari) was collected from the upper part of the granophyric rhyodacite unit that forms the most voluminous component in the volcanic package (Lauri et al., 2003). Zircon grains in the sample A2048 Suosaari are subhedral to euhedral with sharp crystal edges. Many grains contain altered domains and are quite turbid in binocular microscope. However, the LA-MC-ICPMS analyses were made on fresh spots and all data are concordant, yielding an age of 2449±12 Ma (Fig. 1). The age is well compatible with the geologic setting.

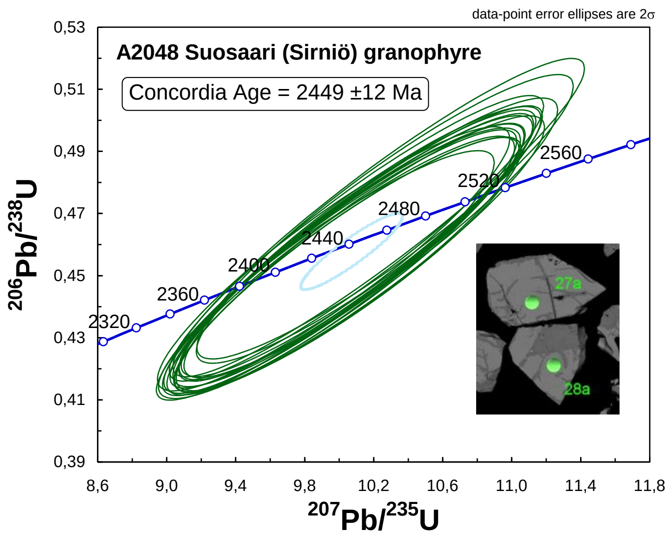

Figure 1. Concordia diagram for sample A2048 Suosaari.

Felsic volcanic rocks with ages of 2.46–2.44 Ga are found throughout northern Finland commonly as the lowermost Paleoprotorozoic unit on the Archean Karelian craton and together they comprise the Salla group (e.g., Manninen et al., 2001; Räsänen and Huhma, 2001). Based on the age and geologic setting the Koillismaa granophyric rhyodacite may be considered as belonging to the Salla group. The new age determination result also confirms the suggestion of Alapieti (1982) that the Koillismaa intrusion intruded the unconformity between the Archean basement and volcanic rocks that were extruded early in the Paleoproterozoic rifting event of the Archean continent, rifting being possibly caused by a mantle plume.

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GLOBAL CRYOGENIAN AND EDIACARAN PALEOGEOGRAPHY: A NEW KINEMATIC AND LITHOSTRATIGRAPHIC MODEL

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Late Neoproterozoic paleogeography has been notoriously difficult to constrain, due to sparse age control among sedimentary basins, orogenic complexity in many regions, and unusually large scatter in paleomagnetic data. We present two contributions herein. First, we produce a revised global kinematic model of craton motions, stemming from the IGCP440 animation (Li et al., 2008) but also incorporating the relative rotation between northern and (western+southern) Australia proposed for Ediacaran time by Li and Evans (2011). Our model is developed using the GPlates software, thus kinematic continuity through time is an essential component of the reconstructional architecture. Second, we make global chronostratigraphic correlations among sedimentary basins, using the most complete list of glacial deposits available to us (Hoffman and Li, 2009; Evans and Raub, 2011) as anchors in the correlations, and we assign sedimentary facies to those deposits in graphic tabular format. Merging these two contributions, we illustrate the sedimentary facies from those units as accurately reconstructed point symbols on a series of global paleogeographic maps at 825, 780, 720, 680, 640, 580, and 540 Ma. These facies-illustrative global paleogeographic maps are undoubtedly inaccurate over many times and places, but they are useful in clearly connecting primary stratigraphic data to the kinematic model. As new chronological and paleomagnetic data become available, we expect that revisions to the maps can be made with relative ease.

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NEW PALAEOMAGNETIC AND GEOCHRONOLOGICAL DATA FROM THE ROPRUCHEY SILL (KARELIA, RUSSIA): IMPLICATIONS FOR LATE PALAEOPROTEROZOIC PALAEOGEOGRAPHY

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The East European craton (EEC), or Baltica, and its components Fennoscandia, Sarmatia and Volgo-Uralia assembled between 1800 and 1700 Ma represent important ‘puzzle pieces’ in global Precambrian palaeogeography (e.g. Bogdanova et al., 2008). The extensive palaeomagnetic study of the Fennoscandian rocks of ~1700-1800 Ma age revealed just three reliable palaeopoles: Hoting Gabbro (Elming et al., 2009), Småland Intrusions (Pisarevsky and Bylund, 2010) and Shoksha Sandstone (Pisarevsky and Sokolov, 2001). Age constraints of two poles are a bit tense. Contrasting 1786 ± 10 Ma U-Pb zircon and 1650-1610 Ma $^{40}Ar/^{39}Ar$ biotite ages for Hoting Gabbro make doubts about the duration of cooling and the age of remanence. The age of Shoksha pole is sandwiched between the 1800 Ma K-Ar glauconite date of the underlying Petrozavodsk Formation (Sokolov et al. 1987) and the 1770 ± 12 Ma U-Pb zircon age of the cutting Ropruchey Sill (Bibikova et al., 1990). Damm et al (1997) and Fedotova et al. (1999) reported preliminary palaeomagnetic data from this sill and their combined palaeopole is significantly different from the apparently coeval 1784-1769 Ma Småland Intrusions pole (Pisarevsky and Bylund, 2010; age by Nillson and Wikman, 1997). A possible reason for this discrepancy might be geochronological.

Ropruchey Sill is a layered lopolith-like body about 170 m thick covering an area of about 4500 km^2. We collected ~200 oriented block samples and cores from various locations including two sites with exposed sill’s contact with country sediments. We also collected geochronological sample, which was processed using the Söderlund and Johansson (2002) water-based method using a Wifley® Table at Lund University and yielded baddeleyites. The baddeleyite grains were then analysed on a Thermo-Finnagan Triton® thermal ionization mass spectrometer at the Natural History Museum in Stockholm. The precise age of 1751 ± 3 Ma was obtained, which is ca. 20 Ma younger than the abovementioned U-Pb zircon age. Our palaeomagnetic data generally confirm preliminary results of

Damm et al. (1977) and Fedotova et al. (1999). This study provides a new reliable well dated 1751 Ma palaeopole for Fennoscandia with implication for the timing of the Baltica's final assembly.

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MAGNETIC MINERALOGY AND PALEOMAGNETISM OF PROTEROZOIC GRENVILLE METAMORPHIC AND IGNEOUS ROCKS OF THE ADIRONDACK HIGHLANDS

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An east-west traverse of the Adirondacks Highlands, northern New York, USA, sampled rocks metamorphosed to granulite facies (T>650°C) at ~1050 Ma during the Grenville Orogeny. Fourteen sites of microcline gneiss give a mean direction of -62.8°, 289.2° with α_{95} = 7.6° and a corresponding pole at 18.6°S, 150.6°E. Metamorphosed anorthosites and associated rocks (N = 14) give a direction of -67.3°, 283.9° with α_{95} = 7.7° and a pole at 25.1°S, 149.0°E. Post-metamorphic fayalite granites (N = 8) give a statistically different direction of -75.8°, 297.0° with α_{95} = 3.9°, and a pole of 28.6°S, 132.3°E. Both normal and reversed polarities are recorded, with reversed sites occurring on the eastern and western ends of the traverse, and normal polarities restricted to the central part. The remanence in the microcline gneisses is carried by ilmeno-hematite, while in the metamorphosed anorthosites and fayalite granites, magnetite is the predominant oxide. Using local cooling curves, and blocking temperatures determined for ilmeno-hematite (< 520C) and magnetite (~ 570C), the age of remanence is ~990 Ma for the granites, ~970 Ma for the metamorphosed anorthosites, and ~960 Ma for the microcline gneisses. Selected studies in the Grenville Province, with age control and known magnetic mineralogy, yielded poles centered on 30°S and 140°E. By comparison, the mean pole positions of the three units studied here support counterclockwise motion on the Grenville loop, with this part of Laurentia moving northward to mid-southern latitudes in the waning stages of the Grenville Orogeny.

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INDIAN PRECAMBRIAN PALEOMAGNETISM: UPDATES AND FUTURE EFFORTS

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Peninsular India is host to numerous mafic and ultramafic intrusive bodies along with several large and relatively undeformed sedimentary basins (Figure 1; Pradhan et al., 2012; Meert et al., 2010). Although somewhat irregularly spaced, the intrusive rocks and sediments span much of Precambrian time and offer tantalizing prospects for documenting the drift history of India. Because of these opportunities, a number of recent paleomagnetic and geochronological studies were undertaken that offer a glimpse into the drift history of the various elements that comprise India and their ultimate amalgamation into Peninsular India. India's role in the formation of ancient supercontinents such as Columbia, Rodinia and Gondwana is revised using these newer data. In this talk, we will offer a comprehensive review of these recent studies along with a preview of newly acquired results (yet unpublished).

Highlights from these new data show that previous thoughts about the position of India within Rodinia (Li et al., 2008) and Columbia (Rogers and Santosh, 2002) are in need of revision. New (and previously published) geochronologic and paleomagnetic data from the Dharwar and Bundelkhand cratons provide additional evidence that most of the so-called Purana basins in India are actually 500 million years older than previously thought (Mesoproterozoic rather than Neoproterozoic). The merging of major cratonic blocks of northern India (Bundelkhand-Aravalli cratons) with the southern cratons (Dharwar, Bastar and Singhbhum) is contentious as some place the unification near the end of the Archean and others place the boundary at the beginning of the Neoproterozoic (~1.0 Ga). Paleomagnetic data from these cratons may help constrain this important continent-building episode. Lastly, published and unpublished data from the Malani Felsic Province and the overlying Marwar Supergroup provide important constraints on the dispersal of Rodinia and the assembly of Gondwana in the Ediacaran to Cambrian interval.

Time Span (Ga) with Paleomagnetic Data Published Since 2001 from India

2.5	**2.4**	**2.3**	**2.2**	**2.1**	**2.0**	**1.9**	**1.8**	**1.7**	**1.6**	**1.5**	**1.4**	**1.3**	**1.2**	**1.1**	**1.0**	**0.9**	**0.8**	**0.7**	**0.6**	**0.5**
	x			**z**	**x**	**x**	**x**		**z**	**z**			**x**	**xyz**	**x**			**xz**		**z**

x-Published
y-In Review or In Press
z-Unpublished

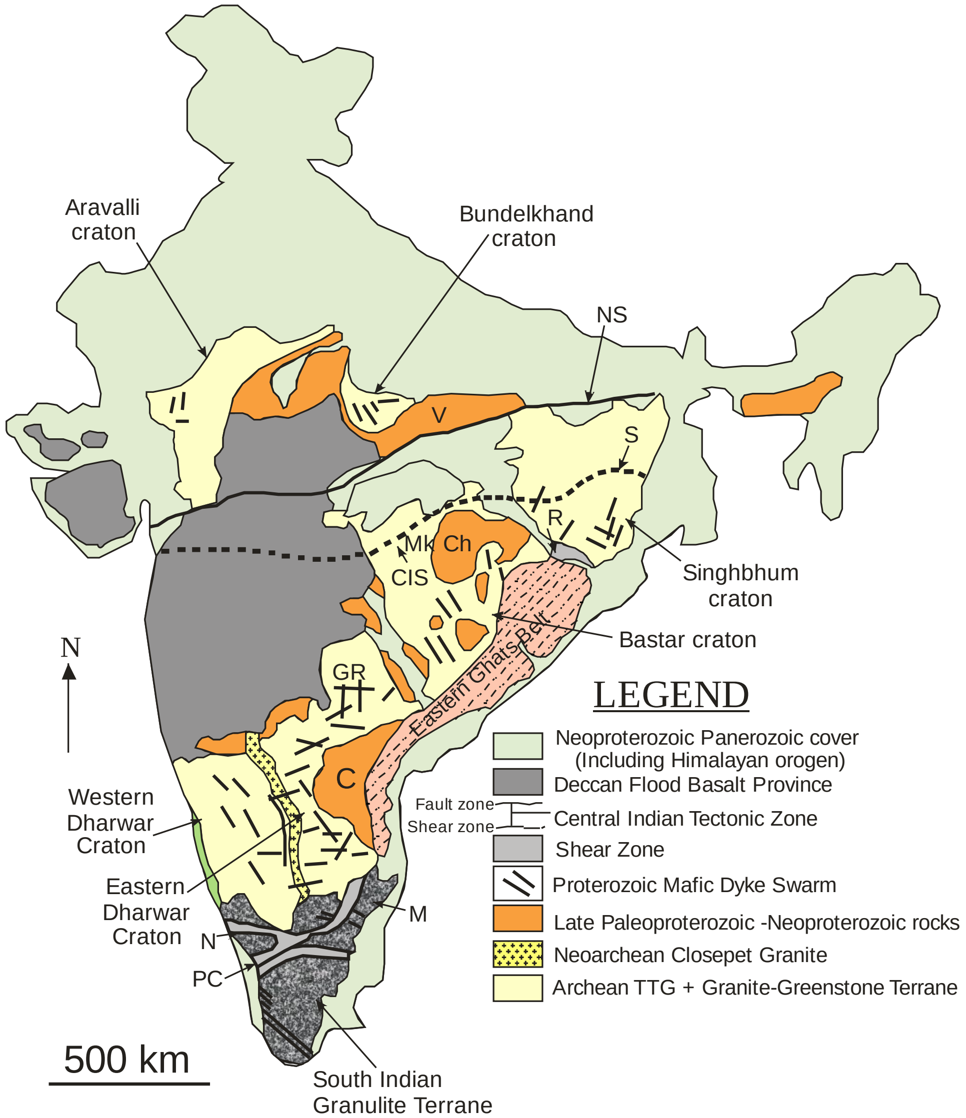

Figure 1. Map of Peninsular India showing the locations of the major cratonic elements, dyke swarms and Proterozoic basins (from Pradhan *et al*., 2012).

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SUPERCONTINENT CYCLES AND THE CALCULATION OF ABSOLUTE PALEOLONGITUDE IN DEEP TIME

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"Traditional models of the supercontinent cycle predict that the next supercontinent—'Amasia'—will form either where Pangaea rifted (the 'introversion' model) or on the opposite side of the world (the 'extroversion' models). Here, by contrast, we develop an 'orthoversion' model whereby a succeeding supercontinent forms 90° away, within the great circle of subduction encircling its relict predecessor. A supercontinent aggregates over a mantle downwelling but then influences global-scale mantle convection to create an upwelling under the landmass. We calculate the minimum moment of inertia about which oscillatory true polar wander [TPW] occurs owing to the prolate shape of the non-hydrostatic Earth. By fitting great circles to each supercontinent's true polar wander legacy, we determine that the arc distances between successive supercontinent centers (the axes of the respective minimum moments of inertia) are 88° for Nuna to Rodinia and 87° for Rodinia to Pangaea—as predicted by the orthoversion model. Supercontinent centers can be located back into Precambrian time, providing fixed points for the calculation of absolute paleolongitude over billion-year timescales."

The preceding paragraph was taken from the abstract of Mitchell et al. (2012), which will be presented herein. We draw attention to the following questions that are most pressing, in our opinion, as arising from the model: (1) Are the paleomagnetically defined oscillations really TPW, or could they be due to unusual plate tectonics, geomagnetic aberrations, or other processes? (2) Does the alternative hypothesis of forever-fixed and stable lower mantle low-shear-velocity provinces (LLSVPs; see Torsvik et al., 2010) make plate kinematics simpler, more complex, or equally complex relative to our model? (3) What do the LLSVPs really represent? (4) What are the dynamic implications of supercontinent amalgamation and dispersal relative to the LLSVPs, according to the alternative hypotheses?

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KIMBERLITES AND LAMPROITES OF THE NORTHERN EAST EUROPEAN CRATON: POSITION IN SUPERCONTINENTAL CYCLES

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The assembly and break-up of supercontinents are the main factors controlling the formation, destruction and modification of lithospheric roots and likely had a dramatic effect on kimberlite and lamproite genesis. Synchronism of the kimberlitic magmatism and phases of supercontinental cycles is widely discussed (Jelsma et al., 2009). Intervals devoid of kimberlite magmatism correspond to periods of continent stability, whereas amalgamation and/or fragmentation of supercontinents are accompanied by the kimberlite and lamproite emplacement (Heaman et al., 2004; Jelsma et al., 2009).

In this work, we attempted to correlate the times intervals of kimberlite and lamproite emplacement on the Northern East European Craton (EEC) with tectonic events within the framework of a supercontinental cycle using new data on the Karelian kimberlite and lamproite.

Six periods (epochs) of kimberlite and lamproite magmatism have been recognized over more than 1.5 Ga on the Northern East European Craton. Two Paleoproterozoic epochs are represented by 1) the oldest (near 2.0 Ga age, Kimozero kimberlite occurrence and 2) 1.7 Ga lamproite and lamprophyre of the Porya Guba. 1.2-1.23 Ga-old lamproite of the Kostomuksha-Lentiira-Kuhmo field were formed during Mesoproterozoic period. Two Neoproterozoic periods produced Kuusamo (0.76 Ga) and Kaavi-Kuopio (0.6 Ga,) kimberlite occurrences. Finally, the Middle Devonian epoch was marked by the formation of the Arkhangelsk kimberlite province (0.37-0.40 Ga) and the Timan kimberlite field.

The ancient Paleoproterozoic kimberlite and Mesoproterozoic lamproite are located in the inner part of the Karelian craton, whereas younger kimberlite occurrences, in contrast, are confined to the craton boundaries and some of them were even generated in off-craton settings (Samsonov et al., 2012).

The appearance of the Mesoproterozoic Kostomuksha lamproite and the Neoproterozoic kimberlite of the Eastern Finland was related to the break-up of supercontinents. During Mesoproterozoic, the EEC was a part of the Columbia supercontinent. Initial rifting marked the beginning of the Columbia break-up that began near 1.4 Ga within the EEC and culminated with emplacement of Central Scandinavian dyke swarm at 1.23-1.27 Ga (Bogdanova et al., 2008). The only occurrence of 1.2 Ga-old magmatism in the inner part of Karelian craton is the Kostomuksha-Lentiira-Kuhmo lamproite. Nevertheless there are numerous evidences, primarily, U-Pb zircon discordia lower intercept ages (Amelin et al., 1995), that 1.2 Ga thermal event spanned the whole craton. Inferred plume nature of this thermal event is supported by geochemical features of the Kostomuksha lamproite, which are typical of anorogenic lamproites and differ drastically from orogenic ones.

Both Paleoproterozoic kimberlite and lamproite and Devonian kimberlite were generated during a supercontinent assembly. The emplacement of the Kimozero kimberlite having U-Pb mantle zircon age of 1.99 Ga (Samsonov et al., 2012) is correlated with orogenic processes in the Svecofennian belt (the presence of 1.95-2.0 Ga detrital zircon indicates the beginning of crust-forming processes at that time (Lahtinen et al., 2002)) in the west and the Kola-Lapland belt in the east of the Karelian craton. On the other hand, this time was also marked by extensive 1.98 Ga-old intraplate basaltic magmatism within the craton. The find of garnet xenocrysts with eclogitic C-type affinity in the Kimozero kimberlite suggests the contribution of slab component to the mantle lithosphere beneath the inner part of Karelian craton.

Tectonic setting of the emplacement of Devonian kimberlite in many respects was similar to that of Paleoproterozoic kimberlite. The Arkhangelsk kimberlite province was formed immediately after Caledonian orogeny which occurred in the west of the EEC and was coeval to the Uralian orogeny in the east of the EEC. Simultaneously plume-induced alkaline magmatism spanned the Kola province.

Metasomatic melts, calculated using the trace-element comositions of xenolithic garnets and clinopyroxene from the Arkhangelsk kimberlite were characterized by elevated CO2- and, probably, K2O-contents. This result may be used as evidence of the presence of recycled crustal component in the lithospheric mantle beneath the Arkhangelsk kimberlite province.

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LATERAL FLOW IN MIDDLE CRUST – EXPERIMENTS FROM SVECOFENNIAN BELT

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Supercontinental cycle build continents and breaks them. Continental collision zones with high topographic relief can develop during supercontinental cycle. In collision zones, plates can rotate the direction of movement locally. When an orogenic belt with high mountain range and thick lithosphere has reached a substantial thickness, the orogen grows outward. A high topographic plateau, which may flow laterally, develops in hinterland. The direction of the lateral flow can differ substantially from the prevailing plate motions. Partial melting is a prerequisite lateral flow (Jamieson *et al*. 2004). Before the widespread melting begins, the crust reaches moderate thickness of 50-70 km. However, if the convergence rate is high, the crust may reach over 70 km in thickness, before melting take place. Thick continental crust remains hot and partially molten for at least 20 My after collision has ceased. The result of large scale melting is observed as large granitic intrusions or migmatites in granitoid belts (Jamieson *et al*., 2011).

The exposed Svecofennian crust (50-65 km) has been suggested to have thickened during continental collision between Archean and Paleoproterozoic crusts (Korja *et al*. 1993), probably at a high convergence rate. It is likely that this thickened orogen experienced lateral spreading in its final stages. The boundary zone between the two colliding continents (Archean and Paleoproterozoic terranes) has had an effect on the geometry of the spreading processes. Korja *et al*. (2009) suggested the central part of the orogen; characterized by Central Finland granitoid complex and associated shear system, to have formed during lateral spreading,

In this study, we have used analogue centrifuge modeling to simulate lateral flow at the boundary zone of Archean and Paloeproterozoic terranes in late stages of Svecofennian orogeny. The analogue models images evolution of the mechanical boundary between the two rheologically different blocks. The experiments were made at Hans Ramberg Tectonic Laboratory in Uppsala University. The materials in the experiment were based on the plastilina modelling putty, which was mixed with acid oil, silicone, sweetener and/or barium sulphate to get the appropriate composition for each layer.

The upper layer is brittle, middle layer is ductile, and the lower layer is more viscous. The layers represent upper, middle and lower crust; respectively. The Proterozoic layers have lower viscosity values than the Archean layers at similar depths. Both the Archean and the Paleoproterozoic blocks have a low-viscous middle crust. The models have been extended laterally in steps. After each extension step the models were photographed and measured and additional material was removed.

Model results show that during extension, the weak Paleoproterozoic middle crust spread laterally resulting in rotation of the boundary between the Archean and Proterozoic blocks. The upper crust was extended by faulting, and the weak Proterozoic middle crust rose upward forming core complexes at surface. The experiments show geometrically similar crustal-scale structures to those observed in other geophysical and geological surveys (Korja *et al*., 2009). Thus it is possible that lateral flow has taken place in the core of the Svecofennian orogen. The experiments indicate that the crustal pieces are not in their postcollisional locations. Especially the upper and middle crustal terranes, but also the lower crustal parts have rotated during lateral flow. This may have implications for the interpretations of paloemagnetic data.

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ULTRA-MATURE QUARTZITES IN SOUTHERN FINLAND: WAS BALTICA PART OF SUPERCONTINENT COLUMBIA DURING 1.85 Ga?

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Quartzites, associated with meta-arkoses and mafic metavolcanic rocks, occur as small deposits in the Paleoproterozoic (1.9-1.8 Ga) Svecofennian orogen of southern Finland. U-Pb zircon age determinations of the quartzites and associated magmatic rocks suggest deposition of quartz-rich sediments during a tectonically stable (intra-orogenic) period 1.86-1.83 Ga, between 1.89-1.87 Ga early Svecofennian contractional deformation and metamorphism, and 1.83-1.80 Ga late Svecofennian deformation and metamorphism. A lateritic paleosol overlain by ultra-mature/mature quartzite was found in three localities that were studied in detail, providing evidence for a 10–20 Ma stable period. At Pyhäntaka, deposition of exhumation-related graywackes after 1.87 Ga, followed by development of a weathering surface and deposition of quartz sands indicate gradual stabilization of the upper crust. A sequence of quartz sands, immature sands, volcaniclastic sands, basaltic rocks and graywackes on top were probably deposited in an evolving intra-orogenic rift basin during crustal extension that may have initiated 1.85 Ga ago.

The ca. 1.85 Ga paleosol-quartzite successions in southern Finland are important indicators for warm paleoclimate and continental-type paleoenvironment and have many similarities with the widespread ca. 1.7 Ga paleosol-quartzite successions in the United States. The paleosol-quartzite successions in southern Finland are more compatible with a continental interior setting with outboard subduction than active margin setting during deposition. This raises the question of the continent: was it the proto-craton Baltica that would later (1.80 Ga) be part of the supercontinent Columbia assembly, or already part of "proto-Columbia" to which the Sarmatia craton collided at ca. 1.83 Ga?

THE SANTA CLARA RAPAKIVI MASSIF: WITHIN-PLATE MAGMATISM IN THE SW OF THE AMAZONIAN CRATON DURING THE FINAL STAGES OF RODINIA AGGLUTINATION

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Cratonic magmatism events in SW Amazonian Craton are characterized by substantial addition of within-plate A-type felsic alkali and mafic magmatism dominantly in the Nova Brasilândia Terrane, Rondônia Tin Province, Bolivia and scattered places in SW Mato Grosso. These are represented by Serra da Providência Intrusive Suite (1.58-1.52 Ga), Santo Antonio and Teotônio Intrusive Suites (U-Pb ages of 1406 Ma and 1387 Ma, respectively), the Santa Clara Intrusive Suite (1080-1070 Ma), Younger Granites of Rondônia (1000-970 Ma), and associated Nova Floresta Formation alkali basalts and mafic dykes (K/Ar ~1000-900 Ma), Rio Pardo Granite Suite (995±15 Ma), Costa Marques Group (Rb/Sr ~1018 Ma), Guapé Intrusive Suite (Rb/Sr 950±40 Ma) and the late kinematic Sunsas granitoids and mafic-ultramafic Rincon del Tigre Complex (Rb/Sr 993±39 Ma), and a number of pegmatites and basic rocks.

The Santa Clara Intrusive Suite (SCIS) was first included in the Younger Granites of Rondonia. However, disparities concernig petrological and geochemical characteristics along with different Rb-Sr and U-Pb ages indicate that the rocks of the SCIS should be considered apart. This intrusive suite comprises different massifs featuring rapakivi texture and bimodal magmatism associations. It is also possible to observe that two different subsuites can be considered within the massif, each of them with its own petrographic and geochemical features, as well as U-Pb ages. One subsuite is subalkaline and mainly composed by porphyritic quartz-monzonites and syenogranites and the alkaline subgroup is mainly composed by alkali-feldspar syenites and microsyenites, alkali-feldspar microgranites, peralkaline microgranites and feldspar-quartz granites porphyry. The alkaline subsuite is intrusive in the subalkaline one. The data available for the rocks of SCIS show that these rocks had their emplacement between 1082 and 1074 Ma.

In this work, several samples of the Santa Clara massif were analysed, and taking into consideration the characteristics observed in field and during petrographic analysis, these granitoids were divided into five different facies: porphyry, isotropic, fine, pyterlitic and wiborgitic facies. The analysed granitoids are intermediate to acid, and range from quartz-monzonites to granites, with some subordinate granodiorites. These rocks belong to the calc-alkaline with high-K and shoshonitic series, and shows metaluminous to slightly peraluminous character. Based on the behaviour of trace elements, these granitoids are typical of anorogenic type-A2 settings, that is, these are related to postcollisional/post-orogenic settings. The geochemical analysis revealed that the granitoids of the Santa Clara massif have high contents of incompatible elements and Rare Earth Elements (REE), with exception of Eu. These rocks also show a slight enrichment in Large Ion Lithophile Elements (LILE) and strong depletion of Sr, as well as a slight fractioning of Ba. These features indicate a strong fractioning of plagioclase and K-feldspar. The negative anomaly of Nb along with a strong depletion in Ti suggests participation of crustal material during the magmatic processes responsible for these granitoids generation.

Isotopic data suggest Paleoproterozoic TDM ages for the Santa Clara massif and negative values of εNd show that these granitoids were derived from partial melting of preexisting crust. This crust represents tonalitic to granodiorites gneisses from the Jamari Complex, which comprises the basement of the area. The U-Pb ages between 1075 and 1061 Ma are compatible with a rapakivi magmatism taken place during the final stages of the supercontinent Rodinia agglutination (1.2-1.0 Ga) and the final stages of the Sunsás Orogenic Cycle in the Amazonian Craton.

Data obtained in this work suggest that during the Sunsás Cycle, extension and thinning of the lithosphere resulted in the generation of basaltic magma derived from the mantle. This mafic magma probably was trapped in the lower crust and cooled, providing the heat source responsible for crustal partial melting. This granitic melt would have gone through fractionation and finally intruded into the basement rocks of the Jamari Complex.

The origin of Proterozoic rapakivi granites is controversial. Most models for this peculiar continental magmatism envisions heat or magma transfer from the asthenosphere to the base of the lithosphere leading to partial melting of the lower crust. The tectonic setting and source of the Mesoproterozoic anorogenic magmatic suites in the SW Amazonian craton revealed by integrated isotopic and geochemical data allow correlation between the accretionary mobile belts and the contemporany continental magmatism (e.g. rapakivi complexes) within the foreland. The continental magmatism may represent the syn-orogenic response to high heat flow in the asthenosphere resulting from oceanic crust subduction, which led to the development of the successive Proterozoic magmatic arcs.

In addition, the western part of the Amazonian craton is a multi-orogenic region formed between 1.8 and 1.0 Ga where successive magmatism, metamorphism, and deformation took place. Therefore, juvenile accretionary events progressivelly amalgamated to the older continental margin during the Paleo and Mesoproterozoic times gives the framework of the evolution of the SW Amazonian craton, like Baltica and Laurentia shields.

NEW U-PB ZIRCON-BADDELEYITE AGES ON ARCHAEAN TO NEOPROTEROZOIC LIPS (MAFIC DYKES) OF THE SÃO FRANCISCO CRATON, BRAZIL, AND THEIR POTENTIAL USE FOR PALAEOCONTINENT RECONSTRUCTION

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Mafic dyke swarms and sills are major components of the São Francisco Craton but their ages and tectonic significance are poorly constrained. This abstract summarizes and discusses new U-Pb ages on zircon or baddeleyite grains from four areas of the craton, i.e. Uauá, Curaçá valley, Chapada Diamantina, and Ilheus.

The Uauá block comprises a basement of ca. 3.1 Ga granulite intruded by three dyke swarms: NW-trending metamorphic tholeiite dykes crosscut by NW- to NE-trending non-metamorphic norite dykes, and NE-trending tholeiite dykes. The two latter dyke swarms were respectively dated at 2726.2 ± 3.2 and 2623.8 ± 7.0 Ma. On the basis of structural relationships the Uauá block is an allochtonous terrane that moved from south to north at about 2.1 Ga during oblique continent-continent collision. Fresh and undeformed tholeiite dykes may be potential targets for palaeomagnetic studies. This kind of data, combined with dyke ages and trends can be used to help reconstruct Neoarchaean supercratons.

The Curaçá dykes and Chapada Diamantina dykes are identical in age, i.e. 1507±6.9 Ma and 1501±9.1 Ma, respectively. The Curaçá dykes display a NE trend and are intrusive into Late Archaean to Palaeoproterozoic granites and gneisses, whereas the Chapada Diamantina dykes are emplaced into sedimentary rocks of the Palaeoproterozoic to Mesoproterozoic Espinhaço-Chapada Diamantina cratonic cover. These two mafic rock occurrences appear to belong to a single magmatic system and their ages are not common in the São Francisco craton, and globally very rare. Besides the São Francisco craton, this 1500 Ma age is only seen in Siberia and Baltica (Ernst et al, Prec. Res 160: 159-178, 2008). Palaeomagnetic data are available for Siberia and corresponding data from the Curaçá and Chapada Diamantina dykes/sills should be sought to demonstrate or not the proximity of the São Francisco-Congo, Siberia and Baltica palaeocontinents.

Along the coast of Bahia state, the Salvador, Ilheus, and Olivença dykes define a radiating swarm that converges on the eastern margin of the São Francisco craton. Previous dating indicated a 924-921 Ma age for the Salvador dykes and ca. 920-930 Ma ages for the Olivença dykes (. Herein we confirm a 926±5 Ma age for the Ilheus dykes. The formerly adjacent Congo craton also contains 930-920 Ma magmatism. This magmatism includes Mayumbian and Gangilia bimodal volcanics in the

West Congolese foldbelt, and also potentially some Congo craton dyke swarms. Together the 925 Ma magmatism of the São Francisco craton and western Congo craton define a 925 Ma large igneous province (LIP) whose plume centre is located at the convergence of the Bahia dyke swarms. This LIP is also associated with the onset of rifting to the south, failed breakup of the São Francisco and Congo cratons, formation of the Macaúbas basin to the south and probably successful opening a small ocean further south. Both Baltica and North China have similar timing of LIP magmatism, are both considered as possible nearest neighbours to the combined São Francisco-Congo craton at this time.

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ANIMATED ASSEMBLY OF SUPERCONTINENT NUNA: GLOBAL OROGENESIS AND METALLOGENY

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In recent decades substantial progress has been made on reconstructing Precambrian supercontinents, including Earth's first supercontinent Nuna (Hoffman, 1997; Meert, 2002; Zhao et al., 2002; Pesonen et al., 2003; Evans and Mitchell, 2011). Most attempts however have suffered from a lack of a complete reference frame, schematic craton topology and in some instances, inherent conflicts in translating blocks across the globe during amalgamation. We resolve these issues using PaleoGIS and structured databases developed for IGCP 509 (Eglington et al., 2009, 2012a,b). We present a new, appropriately scaled, animated reconstruction for *Nuna* between 2.2-1.3 Ga that is consistent with orogenic history and vergence and geodynamic models of ore deposit formation for its constituent deposits (Fig. 1). We use this animation to evaluate the mode and tempo of assembly of Nuna.

Nuna was formed by closure of the young Manikewan ocean between 2.1 and 1.85 Ga. Eleven major Archean cratons were amalgamated (Superior, Slave, Rae, Wyoming, Gawler-Mawson, Volgo-Uralia, Tungus-Margan, Congo, Kaapvaal, Pilbara, Yilgarn) along with 9 ribbon microcontinents (Hearne, MetaIncognita-Sugluk, Karelia-Kola, Sask, Hottah, Buffalo Head, Tarim) and 6 newly assembled blocks (Amazonia, West Africa, Fennoscandia, Reindeer, Proto-Siberia, North China, Proto-Australia). Manikewan and marginal oceans closed diachronously with a distinct lateral progression, focused on initial 'eastern' development of West African and Amazonia and possibly proto-West Australia between 2.1-2.0 Ga (Siberian 1, Magondi, Birimian, Ophthalmian, Eburnian orogenies). Post 2.0 Ga convergence included greater Laurentia (Thelon, Inglefeld, Karelia-Kola, Taltson, Snowbird orogenies) and accretion of microcontinents (Hearne, Slave) and continuing outboard assembly of cratonic nuclei (proto-Siberia, Fennoscandia). Starting at 1.90 Ga, the pace of accretion intensified following a major plate reorganization and plume impingement. Manikewan began to contract in earnest, leading to rapid formation and accretion of numerous arcs and major collisional orogens (Trans North China, NAG, Svecofennian 1 and TransHudsonian, Torngat, Luliang, Barramundi). The spatial pattern and nature of Manikewan closure is consistent with Nuna assembly through introversion.

A second phase of continent accretion 1.88-1.84 Ga, welded the essential core of Nuna (and Laurentia) through additions of the Superior, Wyoming, Sask, Marshfield, Hottah,

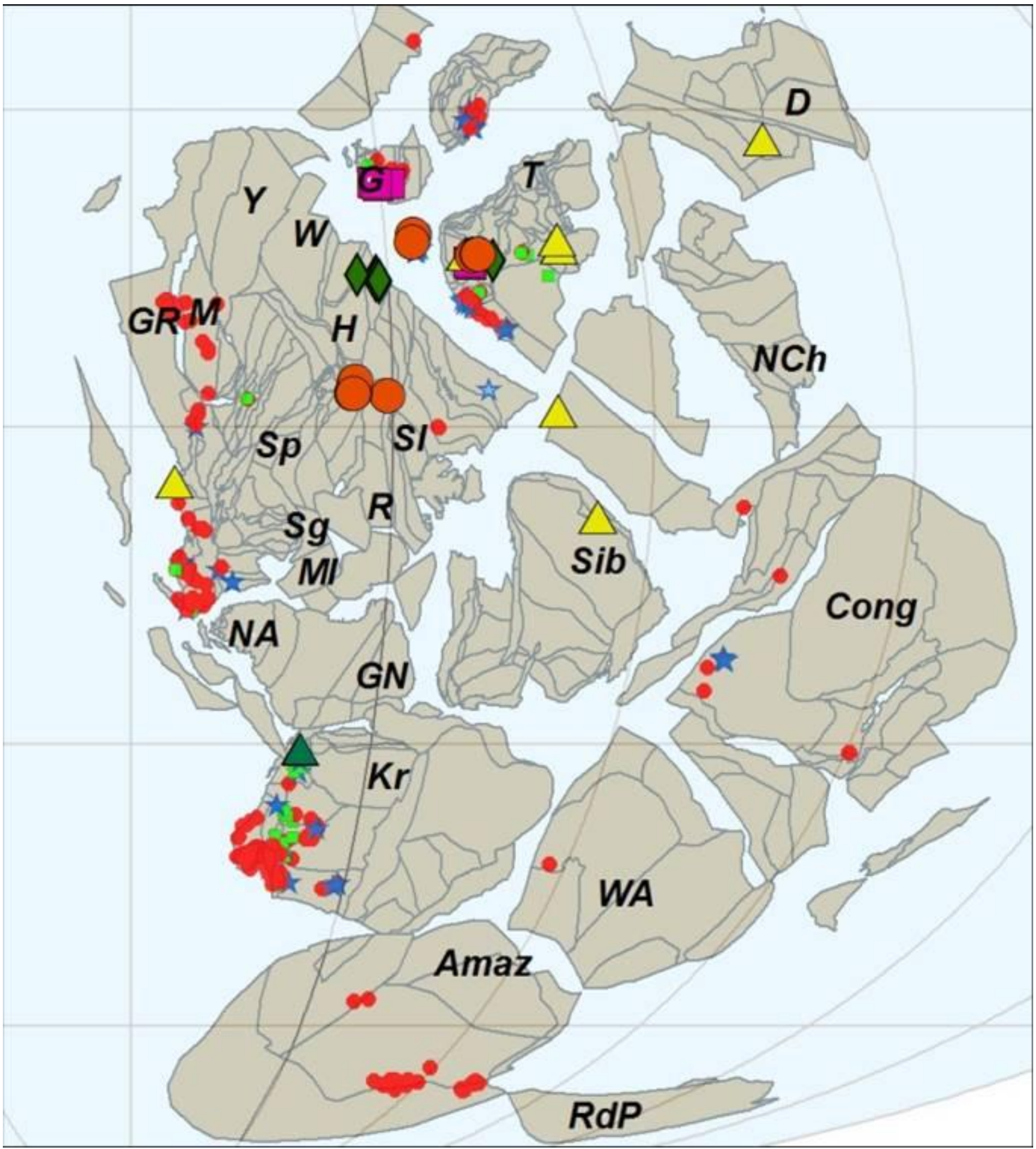

Figure 1: Reconstruction of parts of Nuna at ~1.6-1.46 Ga. Red dots are igneous crystallisation, blue are metamorphic ages and yellow are cooling ages from the DateView database.

North-South Australia cratons. The subsequent terminal collisional phase was focused on the periphery of the supercontinent, with a switch after 1.8 Ga to peripheral orogenesis (Big Sky, Yavapai, Mojave, Gothian, Makkovik) and contemporaneous, repeated episodes of extension and collision in the Proto-Australia sector (Isan, Racklan, Pine Creek), possibly in a Mediterranean-style remnant basin.

Comparison between the metallogenic endowment and phases of Nuna aggregation allow an examination of the effect of aggregation style on mineralization. The interior collisional phase of introverted (or orthoverted) Nuna is distinctly associated with preservation of bimodal-mafic VMS deposits, orogenic-lode gold and magmatic Ni-Cu-PGE, reflecting abundant submarine pericratonic arcs, rapid plate rotation, localized extension and minimal subduction erosion associated with rapid contraction of the Manikewan interior ocean. In contrast the peripheral through breakup phase is associated with little VMS and lode gold, except in the complex dynamics of the Proto-Australia sector, and dominantly IOCG, Sedex, MVT and unconformity uranium deposits. The latter are associated with transient peripheral upper plate coupling or active extension in the supercontinent. This reflects a more exterior style of ocean closure, akin to extroverted (or orthoverted) Rodinia, in which advancing accretion inhibits VMS preservation. We suggest that contraction-related deposits associated with convergent margins correlate strongly in time with periods of supercontinent assembly - not necessarily because rates of subduction were greater but because newly accreted material in interior collisional settings was quickly trapped before it could be consumed.

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CONTINENTS AND SUPERCONTINENTS

Public Lecture

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Maps and especially the shapes of the continents on the surface of the Earth have always been fascinating to scientists. In 1600's a renowned philosopher, Sir Francis Bacon (1561-1626; Fig. 1b), had noticed the similarity in the shapes of the shorelines of Africa and South-America (Fig. 1a) which inspired a German meteorologist and geophysicist Alfred Wegener (1880-1930; Fig. 3a) to think that continents had once been together and later drifted away. An English geophysicist Sir Edward Bullard (1907-1980) was not content with observing the similarity of shorelines but constructed a computer model that proved the African and South-American shorelines to match like pieces of a puzzle (Pesonen and Sohn, 2009 and references therein; Fig. 1c, d).

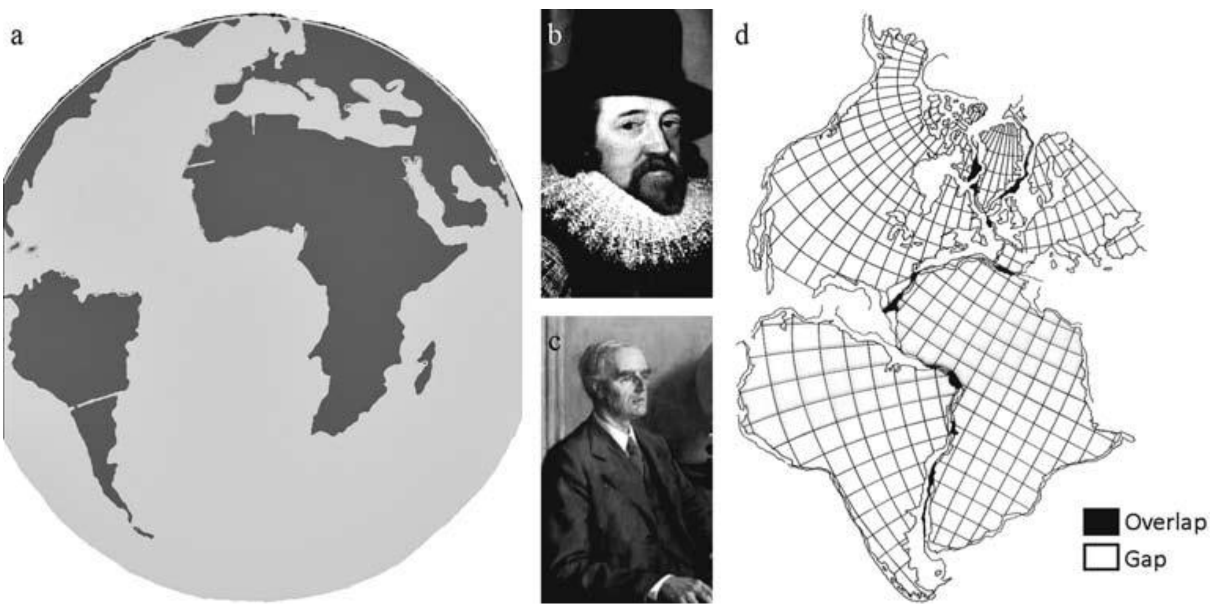

Figure 1. Sir Francis Bacon (b) saw continents as pieces of a puzzle. Note the remarkable similarity of the South-American and African shorelines on a map by Snider-Pellegrin from 1858 (a). In 1956 Sir Edward Bullard (1907-1980, c) with his students created a computer model that matched the shorelines of South America and Africa together with good precision (d).

Alfred Wegener, best known for his continental drift theory (Fig. 3b, model 2), can be described as the "father" of plate tectonics and supercontinent-theories because he proposed that continents have moved horizontally. Before him, continental and oceanic crusts were thought to consist of huge and coherent blocks which moved (uplifted) mainly vertically (Fig. 3b, model 1).

Figure 2. (a) The last supercontinent Pangaia (~350-165 Ma) was preceded by (b) Neoproterozoic supercontinent Rodinia (~1100-750 Ma). Note the Grenville aged (~1100 Ma) orogenic belts encircling Rodinia.

Wegener's hypothesis was revolutionary in the scientific community of that time. He gained support for his ideas especially from geologists while geophysicists opposed the theory mostly due to the lack of the force that moves the continents. Wegener was never able to find a good explanation for the mechanism of continental drift. In 1967 plate tectonics were presented that solved Wegener's problem. Plate tectonics was a radical invention because it shifted the emphasis of research from continental crust to oceanic crust, and simultaneously created the concept of "lithospheric plates" that move horizontally on top of a partially molten astenosphere (Fig. 3b, model 3). The mantle acts as a "lubricant" for the moving lithosphere. The inventors of the 1967 plate tectonics were geophysicists (D. McKenzie, J. Morgan, X. Le Pichon and L. R. Sykes; e.g. Glen, 1982). Their theories were supported by two major preceding observations, namely the spreading of the ocean floor, which was proposed by Harry Hess (1906-1969) and Robert S. Dietz (1914-1995) and the introduction of the transform fault concept by J. Tuzo Wilson (1908-1993).

After plate tectonic theory it took further 20 years until supercontinents were discovered, although Pangaia and Gondwanaland supercontinents have been known among researchers much earlier than the plate tectonics. Supercontinent research went through a major boom in the beginning of 1990's when the first prove of Precambrian supercontinents (Neoproterozoic Rodinia) were discovered (e.g. Hoffman 1991; McMenamin and McMenamin 1990). Recent eophysical and geological observations indicate that the "classic" supercontinent Pangaia (350-165 Ma, Fig. 2a) was preceded by several Precambrian supercontinents. Of these the most well-known are

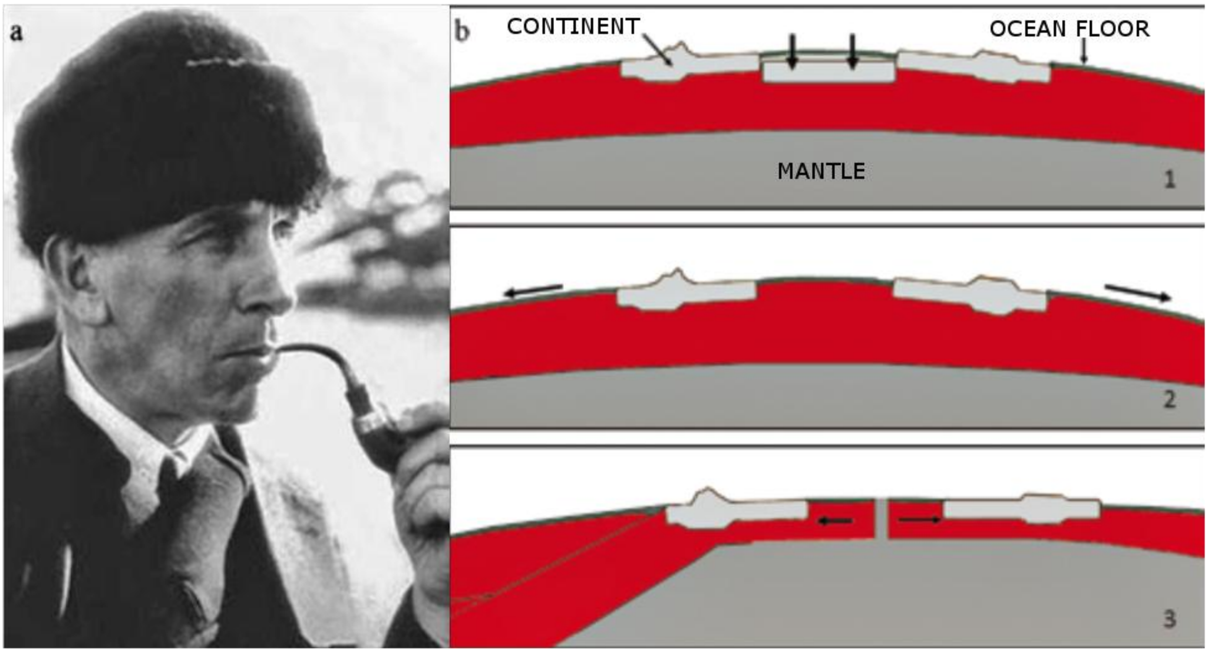

Figure 3. (a) Alfred Wegener (1880-1930), the father of continental drift theory. (b) The developing history of tectonic models. Top: vertical movement model that was the accepted theory in the beginning of 1900's; Middle: the continental drift theory of Wegener; Bottom: plate tectonic theory (from Hallam 1975).

Rodinia (~1100-750 Ma, Fig. 2b), Columbia (also known as Nuna or Hudsonland; ~1950-1300 Ma) and Kenorland (~2700-2450 Ma) (Rogers & Santosh 2003).

Clues of supercontinents

Clues of supercontinents were received after 1950's from several research areas of geological sciences (e.g. Rogers and Santosh 2004). The most important clues were:

1. Paleomagnetic apparent polar wander paths (APWP) from circa 450-180 Ma are significantly different from each other (Fig. 4a). If continents hadn't moved in relation to each other there would be only one "global" apparent polar wander path. When the separate paths are fitted together (Fig. 4b) the continents can be traced back to their positions in Pangaia.

2. Mafic dyke swarms are often intersected at the edges of continents (Fig. 5a). Dyke swarms of same age that today are separated from each other, and found from several continents, can be put to be continuous in supercontinent reconstructions (Fig. 5b). It is likely that a large continental block has been later rifted and the dyke swarms, once being continuous, have therefore been separated.

3. Continents, and the old cratons within, are often surrounded by orogenic belts that in supercontinent reconstructions form encircling or conjugate collision zones. Both cases are found in Pangaia and Rodinia (Fig. 2).

4. Carbon ($^{13}C/^{12}C$), strontium ($^{87}Sr/^{86}Sr$) and oxygen ($^{18}O/^{16}O$) isotope curves often have excursions that have been thought to hint at the formation or the break-up of supercontinents.

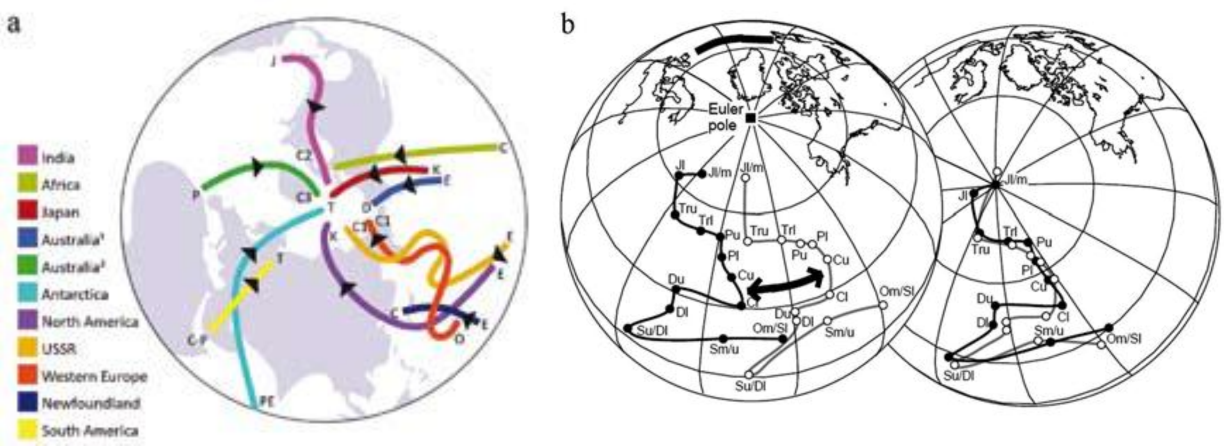

Figure 4. (a) Phanerozoic apparent paleomagnetic polar wander paths of continents (for example between ~450-180 Ma) are significantly different from each other. This is construed as prove of relative movement of continents. (b) On the right is the reconstruction of Europa and Laurentia together with their APWP's.

5. Ophiolite formations of Phanerozoic to Precambrian age represent the ancient oceanic crust that has accreted or obducted to the continental crust. As a good example one of the world's oldest ophiolites, the Jormua ophiolite in Finland, is c. 1.97 Ga old. Similarly so called "paired" metamorphic belts (high P - low T, low P - high T) have been found on island arc terranes or in subduction zones. Also high pressure minerals such as coesite (the high pressure form SiO_2) has recently been discovered from several continents indicating subduction of the plates. The afore mentioned clues indicate of oceanic crust movements and thus of plate tectonics before Pangaia.

6. Geophysical surveys in Precambrian shield areas (e.g. seismic reflection surveys) reveal tilted reflectors in the upper mantle that have been interpreted to be ancient remnants of subducting slices and thus hint to plate tectonic type processes during the Precambrian.

7. Detrital zircon crystals are often found at continental formations whose geologic source remain often as a mystery. It is possible that these "exotic" zircons have originated from another continent or craton that has since drifted away.

8. When continents are fitted together often remarkable continuations are found either in geology (e.g. orogenic belts, dyke swarms, rapakivi or kimberlite occurences), metallogeny, fossil patterns (fauna and flora) or morphology (rivers, rifts). The matching of these features offers a good way to reconstruct former positions of continents ("piercing points"; Rogers & Santosh 2003).

In this presentation the history of supercontinent research is briefly reviewed. A few examples are given to highlight recent accomplishments and new areas of research. The "time-journey" of Baltica from the Archean to present is shown as animation, which also shows the position of Baltica in various supercontinent models.

Tracing supercontinents resembles a puzzle: researchers (geologists and geophysicists) are players and the continents and tectonic blocks are the puzzle pieces. The rules are taken from the Earth's geodynamic processes such as plate tectonics and mantle convection.

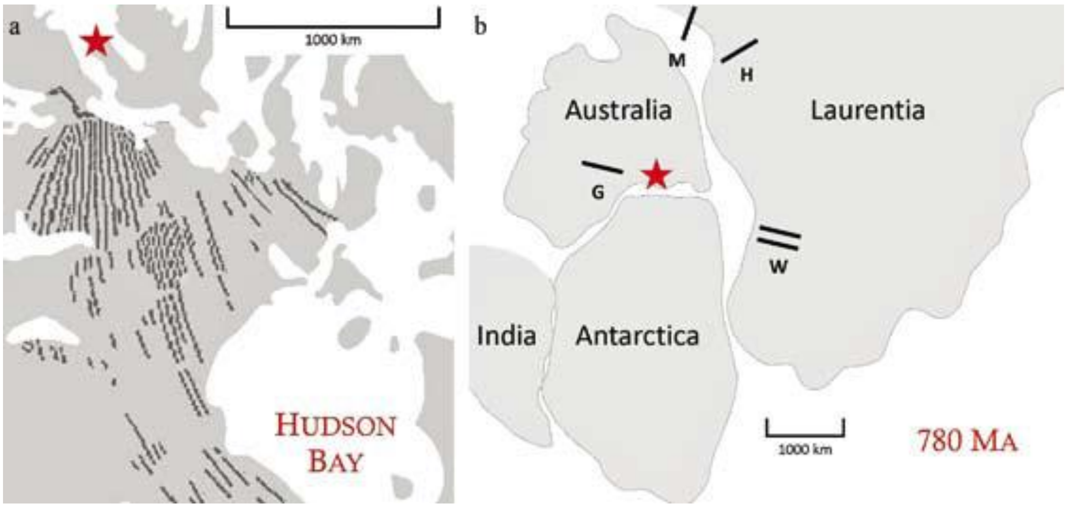

Figure 5. (a) Dyke swarms (as an example the 1.27 Ga old Mackenzie dykes in Canada) are abruptly ended at the edge of the continent and are found again elsewhere. It is likely that the fan like shape of the swarm is associated with a mantle plume (star). (b) An example of the continental reconstruction at ~780 Ma, showing major dyke swarms in several continents pointing to a mantle plume (star) (Park *et al.* 1995).

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A NOVEL PRECAMBRIAN PALEOMAGNETIC DATABASE: THE BASIS FOR ANALYSING SUPERCONTINENTS, GAD AND PSV

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Most paleomagnetic application requires a precise and rationally organized database of paleomagnetic measurements carried out globally. Such applications include paleomagnetic reconstruction, derivation of APW-curves of the cratons, inclination frequency analysis in testing the validity of GAD, analysis of Paleosecular Variation using the scatter of poles, study of reversal asymmetries, and comparison of paleolatitudes of climatically sensitive sediments with those of paleomagnetc data, etc. Here we outline the current status of a long-lasting project to make a novel and user-friendly paleomagnetic database of Precambrian results. The database, originally built in 1986 at the first Nordic paleomagnetic database meeting, has since been updated at intervals of every four years. The "new form" (Excel spreadsheet-form) of this data base got a new stimulus in the early 2000s when the Yale University group (David Evans) joined with Helsinki University group in formalizing the new database, drawing extensively from the most recent published update to the Global Paleomagnetic Database (GPMDB; Pisarevsky, 2005).

The previous databases (such as GPMDB), although widely used and well serving the paleomagnetic community in many ways, suffer from the following shortcomings: (i) the data have not been ranked according to a well-accepted reliability scale, so novice users cannot easily distinguish reliable from unreliable data; and (ii) ages of poles, especially from early studies, have not been systematically updated to reflect new geochronologic constraints. We have produced automatic formulas for applying Van der Voo's (1993) quality criteria 1-6 to all entries, although we have omitted his criterion #7 because that is difficult to apply to Precambrian data. We also provide new isotopic ages to a majority of the >2000 entries. We have split, whenever possible, the paleomagnetic entries into normal" (N), "reversed" (R) and "combined" (N+R) subentries by recalculating the published data into two polarity groups when it is obvious. We note here in passing that the terms "Normal" and "Reversed" are not meant to be viewed in absolute terms since for Precambrian era the polarities are basically unknown due to long gaps in the APW-curves. Therefore, a warning is given here for any attempts to compare N or R data from one continent to another, or even within one craton. In the case of every "continent", we have subdivided the entries into cratonic terranes. This is important not only in reconstructing ancient supercratons or supercontinents, but also in spatio-temporal binning of the data in the inclination analysis of the validity of GAD (see Veikkolainen et al., this volume). We have also calculated several other useful parameters such as the inclination asymmetry parameter (/I/) to describe the departures from a perfect symmetry, the S-parameter (scatter

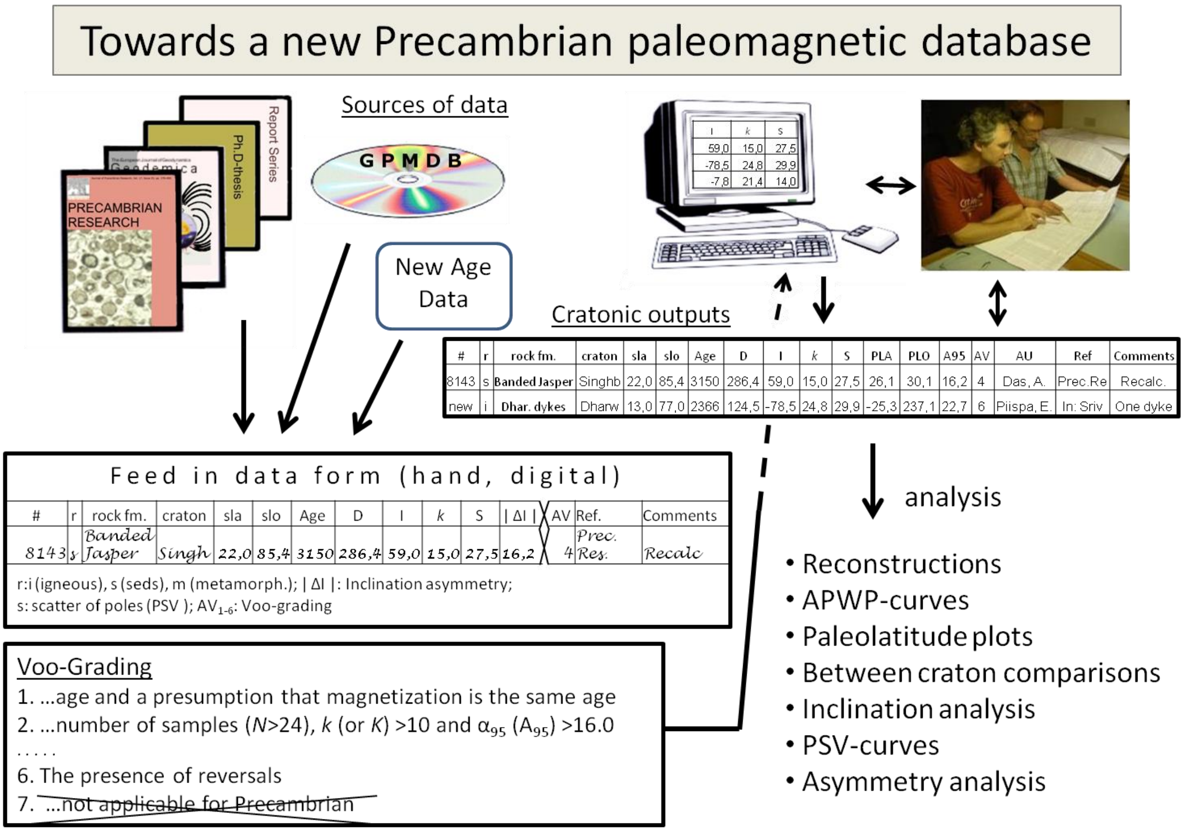

Figure. 1. A schematic view on how the data from various sources are fed-in to the novel Precambrian spread-sheet database.

of poles) to give us a way to study paleosecular variation (PSV), etc.

The current database is in a form of Excel-spreadsheets. Our aim is to link this database to GPMDB and other global databases, as well as to download it into our home page.

In the presentation, we outline the hierarchy of the current database with several applications.

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PALEO-MESOPROTEROZOIC SUPERCONTINENTS – A PALEOMAGNETIC VIEW

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The importance of supercontinents in our understanding of the geological evolution of the Earth has been recently discussed in several articles (e.g., Rogers and Santosh, 2004 and references therein). Geological processes linked to the existence of supercontinents include concepts such as large igneous provinces (LIPs), mantle superplume events, low latitude glaciations and the high obliquity-theory of the rotation axis, the "Snowball Earth" hypothesis, carbon isotope excursions, fragmentation of continental dyke swarms, truncations of tectonic belts and major, matching of conjugate orogenic belts, episodic nature of distributions of magmatic activities, discoveries of Precambrian ophiolites in several cratons, and the concept of true polar wander (e.g., Pesonen et al. 2012 and reference therein).

Various geological and geophysical evidence show that at least two supercontinents, Columbia and Rodinia, existed during the Paleoproterozoic and Mesoproterozoic eras. In this study, updated paleomagnetic and isotope age data has been used to define the amalgamation and break-up times of these supercontinents.

Before putting the ancient continents to a supercontinent assembly, we have tested the validity of the geocentric axial dipole model (GAD) of the Paleo-Mesoproterozoic geomagnetic field using four methods: (i) the inclination analysis, (ii) the paleosecular variation (PSV) technique, (iii) study of internal consistency of poles and (iv) study of reversal asymmetry. The tests yield support to the GAD-model, but do not rule out a ca. 10% non-dipole (octupole) field. In the whole of Proterozoic, Columbia and Rodinia were predominantly in moderate to low paleolatitudes, but during the Paleoproterozoic some parts of Columbia, notably India (Dharwar craton) and Australia (Yilgarn craton), occupied polar latitudes. In the Paleoproterozoic, there were unexpected low-latitude glaciations. The pre-Columbia orogenies were due to a complex set of collisions, rotations and transform or strike slip faultings that caused the orogenic belts to appear obliquely. However, mo prominent difference was observed between paleomagnetically derived and recent geologic models of Columbia. The final amalgamation of Columbia didn’t happen until ca. 1.53 Ga. Columbia broke up at ca. 1.18 Ga during several rifting episodes, followed by a short period of independent drift of most continents. The amalgamation of Rodinia didn’t take place until 1.10 - 1.04 Ga.

In this paper, we use the updated palaeomagnetic database (Pesonen et al., 2012, this volume), combined with new geological information, to define the positions of the continents during Paleoproterozoic (2.5 - 1.5 Ga) and Mesoproterozoic eras (1.5 - 1.04 Ga). We do the reconstructions relying mainly on isotopically (U-Pb) dated high quality palaeopoles since this method provides strict information of ancient latitudes of the cratons throughout the Proterozoic. We focus on Paleo-Mesoproterozoic reconstructions at seven time slots, 2.45 Ga, 1.88 Ga, 1.77 Ga, 1.63 Ga, 1. 53 Ga, 1.26 Ga and 1.04 Ga, respectively, but represented by at least four or more continents per each age bin.

a.) The data come mainly from the cratonic areas of the largest continents or continental fragments which are Laurentia, Baltica, Amazonia, Kalahari, Congo, São Francisco, India, Australia, North China, West Africa and Siberia (Fig. 1). The smaller cratons or "microcontinents", such as Rio de la Plata, Madagascar, South China, Taymyr etc. are not included due to lack of reliable data from the investigated period 2.45 - 1.04 Ga. Neither included in the current analysis are the large Saharan craton in Africa, several small South American (e.g., Pampia, Paraná), Indian (Eastern Ghats), East Antarctican (Mawson, Rayner, Wilkes), and East European (Volgo-Uralia) cratons or microcontinents, since no realiable Paleo-Mesoproterozoic paleomagnetic data are so far available from them.

b.) The data come from the updated Precambrian paleomagnetic compilation done at the University of Helsinki and at Yale University (Pesonen and Evans, 2011). Every entry has been coded to its source continent/craton and also rated according to grading scheme by Van der Voo (1990) with seven steps (Q_{1-7}). We used six out of seven grades since the last grade (Q_7) cannot be applied meaningfully to Precambrian data. In general, we accepted data with total Q higher or equal to 4. However, occasionally we accepted entries with a smaller Q if there are reasons for this, such us new ages or new paleomagnetic information. The used data are compiled in Appendix 1.

PALEOMAGNETIC RESULTS OF WAJRAKARUR KIMBERLITES AND OTHER MAFIC DYKES, DHARWAR CRATON, INDIA

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The Eastern Dharwar Craton of India occupies three distinct kimberlite fields of which the Wajrakarur field (WKF) includes the most abundant intrusions and also most of them are diamondiferous. The WKF consists of four clusters of kimberlites: the Wajrakarur-Lattavaram, Chigicherla, Timmasamamudram and Kalyandurg fields. Radiometric ages of the WKF kimberlites vary considerably from 840 to 1350 Ma (Chalapathi Rao et al. 2012) but the ages seem to center in ~ 1090 Ma. Since this age is crucial for investigating the onset of Rodinia Supercontinent (Pesonen et al. 2012) we decided to study paleomagnetic, rock magnetic and petrographic properties of WKF to constrain the position of Dharwar Craton at the amalgamation of Rodinia.

Table 1. Summary of petrophysical data of Wajrakarur kimberlites and mafic dykes

Site	Area	Rock type	Facies	B/N	D	X	NRM	Q	Strike	W	Comments
			Kimberlites (~1.1 Ga)								
P1	Wajrakarur	G1 kimb.	diatreme	*4/4	2912	610	17.6	0.73	?	?	Pipe, xenoliths
P2a	Wajrakarur-Ananthapur	G1 kimb./ UML?	hypabyssal	*10/32	2963	49740	10625	3.1	NE	30	In-situ brecciation
P2b	Wajrakarur	baked gneiss	wall rock	1/*3	2760	8170	181	0.61			Central gneiss
P4	Wajrakarur-Lattavaram	G1 kimb.?	hypabyssal	*4/6	2963	25114	639	0.7	NE	50	~ Dyke, boulders?
P12	Wajrakarur-Chintalapalle	G1 kimb./ UML?	hypabyssal	*3/7	2967	28743	774	0.62	?	?	Dyke, xenolites
C5	Wajrakarur-Chigicherla	G1 kimb.	hypabyssal	*6/4	2739	69556	3593	1.19	NNE	?	Fragmental kimberlite
Mean	Wajrakarur kimberlites			*5/63	2884	30322	2638	1.16			
P5	Wajrakarur-Lattavaram	G1 kimb./ UML?	hypabyssal	*6/19	2900	41433	883	0.54	~E-W	4	um. Lamprophyre
			Olivine ? diabases (~2150-1880 Ma?)								
LA	Wajrakarur-Lattavaram	diabase	dyke	1/3	2978	15173	1719	2.83	E-W	4	Ophitic db., chilled m.
LB	Wajrakarur-Lattavaram	diabase	dyke	1/2	3052	2580	380	3.66	NW-SE	80	Coarse diabase
Mean	Wajrakarur olivine diabases			*2/5	3015	8877	1050	2.25			
			Mafic dyke (strike NW-SE)								
KN	Wajrakarur-SW Kurngol	basaltic	dyke	*2/3	2886	47315	936	0.5	NW		Possibly apophyse

Site: pipe or exposure according to Chalapathi Rao et al. (2012); G1 kimberlite type according to La Maitre (2002), UML ultra-mafic lamprophyre; B/N number of samples/specimens; D density (kgm^{-3}); X susceptibility (10^{-6} SI); NRM intensity of Natural Remanent Magnetization (mAm-1); Q Koenigsberger ratio; W width (m) of exposure.

Petrophysics and petrology. All of our kimberlite sites have been considered as group 1 kimberlites (Chalapathi Rao & Srivastava 2009) being volatile rich, feldspar-free potassic ultrabasic rocks (Le Maitre, 2002). The recent discussion, however, rise a questions, whether some of these could represent ultramafic lamprophyres (UML). The UML´s bear similar features to kimberlites and further, the interpretation of the WKF intrusions is hampered by secondary alteration common in kimberlitic rocks, especially Proterozoic ones. The mean densities vary from 2739 to 2967 kgm^{-3}

being typical for G1 kimberlites. The susceptibilities show considerable variations and the Q-values range from 0.6 to 3.1.

Rock magnetism. Thermomagnetic curves reveal that low Ti-magnetite is the main carrier with Tc ~ 560-575ºC and distinct Hopkinson-effects. Hysteresis data indicates SD to PSD grain-sizes of the carriers. This is somewhat surprising since AF demagnetization data show often unstable or scattered behaviour.

Paleomagnetism. Thermal demagnetizations showed strong alterations during treatments and therefore AF-demagnetizations were mostly used. The results were generally quite scattered and often dual polarities (N, R) are superimposed yielding complex orthogonal plots. The characteristic S or SW downward pointing component (here denoted N-polarity) were, nevertheless isolated from six kimberlite exposures (Table 2). It is possible that three sites (P2, P4 and C5) show dual polarities but the R-polarity directions, departing clearly from antipodality, are poorly determined and are not included in the final mean. It is noteworthy that previous paleomagnetic results reveal also scattered, mainly S or SE pointing dual polarity directions with similar asymmetries (Table 2).

Table 2. Paleomagnetic data of Wajrakarur kimberlites (~1.09 Ga) and mafic dykes [Lat. = 15.05 °N, Long. = 77.4 °E]

Unit	Type	B/N	P	D	I	k	α95	Plat	Plon	A95	Comments
				kimberlites							
P1	G1	1/*5	N	233.5	78.4	6.5	32.4	-1.3	239.6		
P2	G1/UML	1/*5/	N	235.7	70.7	76.2	8.8	5.7	229.0		
P2	G1/UML	1/*1/	R	203.7	-75.5	67.5	15.1	-39.3	271.3		scattered
P4	G1/UML	1/*4	N	256.1	86.1	4.3	50.1	-13.1	249.7		
P4	G1/UML	1/*3	R	161.0	-43.5	8.1	46.4	-69.4	200.6		scattered
P12	G1/UML	1/*5	N	261.5	77.2	6.2	33.9	-10.2	232.8		
C5	G1/UML	1/*2	N	109.3	53.2	5.7	42.3	7.0	309.6		
C5	G1/UML	1/*3	R	276.7	-84.3	24.1	25.7	-13.5	268.9		poorly determined
P5	G1/UML	1/*6	N	158.5	68.0	8.3	24.6	21.3	271.7		
				baked gneiss							
P2		1/*3	N	73.9	78.8	4.2	69.1	-19.9	279.5		
				olivine diabase dykes							
LA		1/*3	N	72.8	22.2	118.7	11.4	19.4	160.2		~2.1 Ga?
				mafic dyke (NW - SE)							
KN		1/*2	N	67.4	1.9	-	-	22.1	172.6		~2.1 Ga?
Mean WKF kimberlites (*)		6	N	181.1	80.9	16.4	17.0	2.7	257.1	9.5	this work
Mean WKF kimberlites (*)		3	R	177.6	-71.2	10.1	41.0	-49.3	255.4	8.2	this work, scattered
				previous works of WKF-Kimberlites							
W1		2/*12	R	104.0	-39.0	16.5	11.0	-18.3	186.1	10.1	Anand (1971)
W2		2/*21	N	158.0	42.0	1.6	40.0	45.4	286.4	38.4	Anand (1971)
W3		2/*22	R	156.4	-71.1	25.2	6.3	-45.5	238.5	10.8	Miller et al. (1994)
W4		*2/*12	N	179.3	44.6	178.0	18.8	48.7	258.4	18.8	Poornachandra Rao (1984)
W5		*7/?	R	106.9	-49.9	8.9	8.9	-22.1	194.7	9.7	Venkateshwarlu (2010)

G1/UML see Table 1; B/N number of samples/specimens; N(R) normal(reversed) polarity; D, I declination, inclination of ChRM; k Fisher (1953) precision parameter; α95 95 % confidence circle of mean direction; Plat, Plon latitude, longitude of the paleomagnetic pole; A95 95 % confidence circle of the pole. W1 to W5 are data of previous works on WKF kimberlites - see References.

Our ChRM's are, however, distinctly steeper (down or up) and more westerly than previous results. We attempted at site P2 a baked contact test but the result is inconclusive: the baked "central" gneiss (~2.6 Ga) reveals direction (D~74º, I~79º) which is not far from the kimberlite direction (D~236º, I~71º), nor from those of the unbaked "Central gneiss" or charnockite rocks (Piper et al. 2003). The grand mean pole (Plat=2.7ºN; Plon=257.1ºE, A95=9.5º, N=6 sites) of WKF this study (six N-polarity data) represents a robust paleomagnetic pole for Dharwar craton at 1.09 Ga.

Onset of the Rodinia supercontinent. The new ~1.09 Ga grand mean pole of WKF suggests that Dharwar craton has located at higher paleolatitude ($\lambda_{1.09}$ = 72±7º) than previously thought (e.g. Pesonen et al. 2012). The new high latitude pole of Dharwar at 1.04 Ga requires very rapid latitudinal motion for Dharwar craton during 1.09-0.9 Ga.

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PALEOMAGNETISM, GEOCHEMISTRY AND GEOCHRONOLOGY OF THE MESOPROTEROZOIC BARAGA - MARQUETTE AND THUNDER BAY DYKE SWARMS

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The Baraga-Marquette (BM) and Thunder Bay (TB) dyke swarms were emplaced as a part of the ~1.1 Ga Midcontinent rift system (MRS). The dyke swarms are located on the opposite sides of the MRS axis and generally strike parallel to the axis. Here we report the current results of our on-going paleomagnetic, geochemical, and geochronological investigation of both dyke swarms in order to better understand the evolution of the MRS. For this study, a total of 46 dykes (17 from BM and 29 from TB) have been sampled. Both BM and TB swarms yield stable normal and reversed remanent magnetization directions, for which a primary origin is supported by positive baked contact tests (e.g. Robertson and Fahrig, 1971; Pesonen and Halls, 1979; Pesonen, 1979; this study). However, the reversely magnetized dykes have characteristic directions of magnetization that are about 40 degrees steeper in inclination than their normally magnetized equivalents, while declinations show the expected 180 degree relationship. The corresponding paleomagnetic poles suggest the movement of Laurentia from higher latitudes towards intermediate latitudes during the formation of the MRS, in general agreement with previous studies.

Field observations (cross-cutting relationships, the truncation of ridges, and mapping of textures distinct to each dyke) suggest the following emplacement sequence for the TB dyke swarm: the Pigeon River dykes, followed by the Cloud River dykes and, lastly, the Mount Mollie dyke. The available radiometric dates indicate that the Pigeon River dykes were emplaced within a 60 m.y. interval between 1141 ± 20 Ma and 1078 ± 3 Ma (the Rita Bolduc and Arrow River dykes, respectively; Heaman et al., 2007). However, despite a discrepancy in the emplacement ages, the geochemical compositions of the Pigeon River dykes are tightly grouped (Hollings et al., 2010) suggesting perhaps a shorter emplacement interval. No radiometric ages have been reported for the BM dykes. However, their cross-cutting relationships, petrological analyses and different magnetic polarities suggest at least two pulses of dyke emplacement activity. In neither the BM nor TB swarms, have reversely magnetized dyke been observed to cut a normal polarity dyke. In TB swarm both reverse and normal polarity dykes have been observed to cut the reverse polarity Logan sills.

The BM dykes display broadly similar trace element characteristics to the TB dykes, albeit some subtle differences are present within the BM swarm. Both the normal polarity Baraga and Marquette dykes have slightly higher La/Sm_n and Gd/Yb_n values, than the associated reverse polarity dykes. This discrepancy may be attributable to normal polarity dykes having undergone a greater degree of crustal contamination than the reverse polarity dykes, a hypothesis consistent with the reverse polarity dykes pre-dating the normal polarity dykes, the latter having spent more time in a staging chamber and assimilating more crustal material.

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CROSS-CUTTING PROTEROZOIC DYKE SWARMS OF DHARWAR CRATON, INDIA

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The Proterozoic mafic and alkaline dyke swarms exposed in the Dharwar craton (Southern India) are of special interest because the craton has been a principal constituent of several ancient supercontinents. The peaks in dyke emplacement activity in the craton occurred at 2.37, 2.18, and 1.89 Ga (e.g. Halls 1997; French et al. 2008; French et al. 2010; Kumar et al. 2012). Younger swarms in the eastern Dharwar have been observed in the form of kimberlites, alkaline dykes, and rhyolites dated at 1.20 to 1.00 Ga (e.g. Ernst, 2008 and references there in). These mafic and alkaline magmatic events have been linked to mantle plume activity associated with the formation of large igneous provinces and to episodes of the crustal extension leading to rifting and supercontinent break-up. Our ongoing multi-disciplinary study of the Dharwar dyke swarms combines paleomagnetism and geochemistry with interpretation of the dyke emplacement order based on aeromagnetic and satellite images and magnetic modeling (Fig. 1). Herein, new paleomagnetic results and ground magnetic survey data are presented along with their geodynamical implications. A total of 260 block and drill samples were collected from 33 dykes, and their baked and unbaked host rocks. The paleomagnetic data, with distinct mean directions, allow us to refine the apparent polar wander path for the Dharwar craton during the Proterozoic. Possible plate reconstruction scenarios, based on combining our new data with existing paleomagnetic data from other cratons, are discussed. The stability and morphology of the Precambrian field is also tested by calculating the strength of paleosecular variation from the directional paleomagnetic data obtained from the Dharwar dyke swarms.

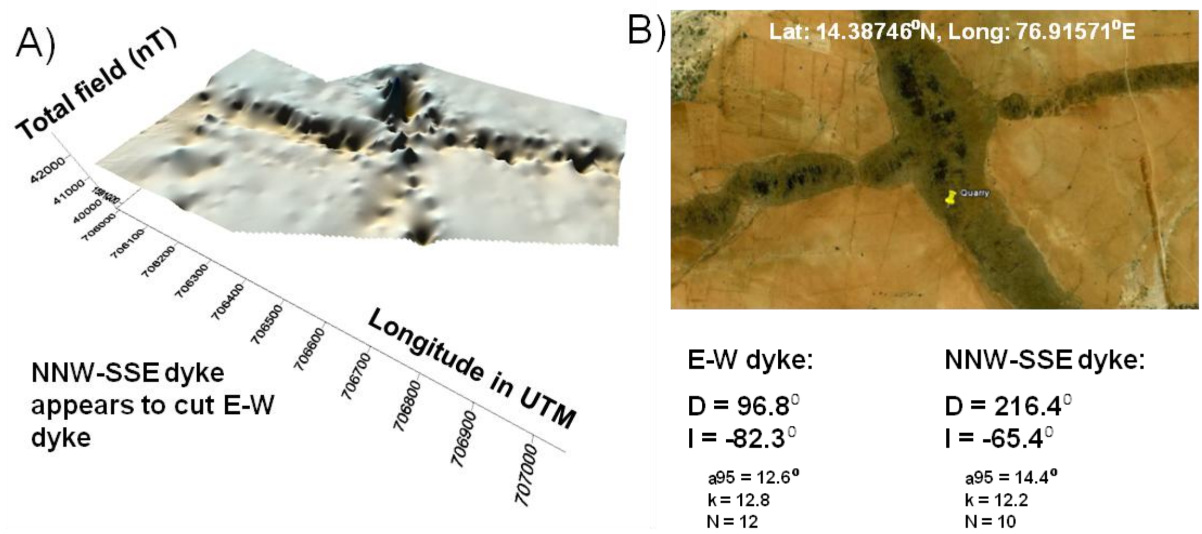

Fig. 1. A) A 3-D ground magnetic survey visualization of NNW-SSE trending dyke cutting E-W trending dyke in Tippanapalle. B) Googlemap image of the cross-cutting along with the characteristc mean paleomagnetic directions for each dyke. D: declination; I: inclination; a95: the radius of the 95 % circle of confidence about the mean magnetization direction, k: precision parameter, N: number of samples.

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PALEOMAGNETISM OF LAMPROPHYRE DYKES NEAR MARATHON, ONTARIO, CANADA - EARLY STAGE OF MIDCONTINENT RIFT VOLCANISM?

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The Mesoproterozoic Midcontinent rift system (MRS) around the Lake Superior region in North America is a failed ocean formed by continental rifting. The main competing theories for the formation of the MRS include mantle plume, plume clusters and back-arc basin settings. The volcanism has been divided into four stages extending from about 1140 to 1087 Ma, with a gap between 1140 and 1115 Ma. Thin ~1140Ma lamprophyre dykes (Queen et al., 1996) coeval with the Abitibi diabase dyke swarm at 1141 Ma (Ernst and Buchan, 1993) possibly represent the first magmatic stage of the MRS. They both fan from Lake Superior and both have alkali nature.

We did a pilot paleomagnetic study on five N-S to NW-SE trending lamprophyre dykes near Marathon, Ontario in Canada. Four of the five lamprophyre dykes showed typical Keweenawan reversed polarity (Figure 1) with a mean characteristic component of D = 109.8°, I = -68.4°, α95 = 14.9 °, k = 39.1. Positive baked contact test against Archaen greywacke supports the primary origin of the magnetization. This places the 1140 Ma lamprophyre paleopole at 47.6°N, 142.8°W, α95 = 24.4 °, k = 15.1. Interestingly most of the Marathon dykes were of reversed polarity whereas most of the Abitibi dykes were normal (Ernst and Buchan, 1993). The five normally magnetized units from the Abiti dykes yielded a similar mean paleomagnetic pole at 42.8°N, 151.5°W, dm = 16.3°, dp = 12.5°. The opposite paleomagnetic directions and similar emplacement ages support for a reversal around 1140 Ma. We do note that data set from the Marathon dykes is not adequate for complete conclusions and more sampling is needed, especially from the other end of the fanning swarm near Kapukasing about 300 km east from this study's sampling sites.

The apparent fanning from the Lake Superior for both of these dyke swarms, the alkali nature of the swarms, coeval emplacement ages and similar paleomagnetic directions support the connection between these dyke swarms. If Marathon and Abitibi dyke swarms were the precursor to the MRS volcanism they could represent the first plume cluster event of the multiple plumes such as is suggested with the Matachewan and Mistassini dike swarms where a number of plumes have erupted in a spatially restricted area.

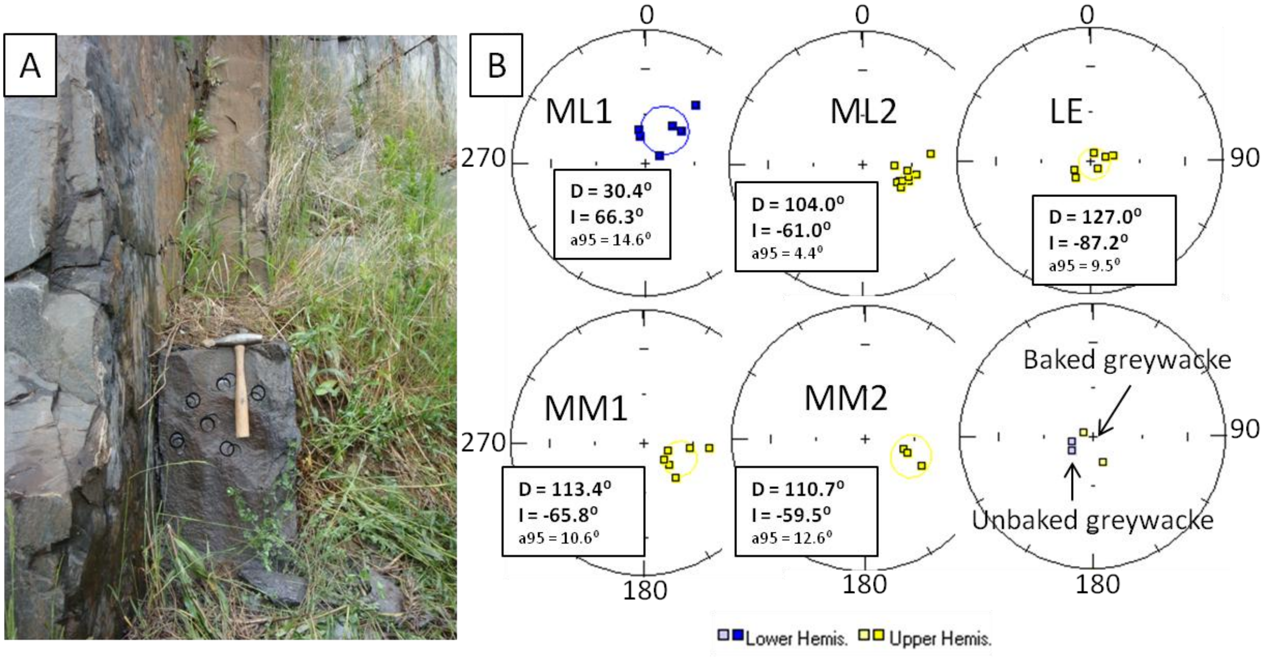

Figure 1. A) The narrow northerly trending ML2 aillikite lamprophyre exposed in a road cut along the Highway 17 near Marathon, Ontario, Canada. The size of the hammer is about 20cm. B) The paleomagnetic directions of the 5 studied lamprophyre dykes and a positive baked contact test from dyke MM1 on equal area stereoplots. The blue/yellow symbols refer to down (up) directions. The mean paleomagnetic directions of each dyke are stated in the small boxes where D: declination, I: inclination and a95: the radius of the 95 % circle of confidence about the mean magnetization direction.

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MESOPROTEROZOIC SUPERCONTINENT - PALEOMAGNETIC SYNTHESIS AND GEOLOGICAL CONSTRAINTS

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The hypothesis of Precambrian supercontinents has been widely debated. The UNESCO IGCP 440 project "Rodinia Assembly and Breakup" (Bogdanova et al., 2008) marked a significant breakthrough in our understanding of the youngest Precambrian supercontinent, Rodinia. The next target is Mesoproterozoic. The time between 1600 Ma and 1200 Ma is of a particular interest. Unlike those of older and younger times, rocks of this age lack evidence of glaciations or of any extreme $\delta^{13}C$ excursions (Bekker et al., 2001), but the indicators of warm climate – carbonates and evaporates – are abundant. Were these strata deposited in low latitudes at the time of their formation, or did the whole Earth have a warm climate for about 400 m.y.? In the latter case, this time interval may represent the oldest and longest 'greenhouse period' in the Earth's history. The number and extent of identifiable continental passive margins was surprisingly low during this time interval (Bradley, 2008). Is this related to a supercontinent, or is it merely the matter of preservation? There are few indications of new continental crust formation, but rift-related intraplate magmatism was extensive. An increasing number of publications indicates a growing interest to a hypothetic pre-Rodinian supercontinent variously called Nuna, Columbia, or Hudsonland (e.g., Hoffman, 1997; Meert, 2002; Pesonen et al., 2003). One of the main reasons for this hypothesis lies in the widespread evidence for 2.1-1.8 Ga orogens in the majority of continents (e.g., Zhao et al., 2004) and the suggestion that some or all of these orogens resulted from a supercontinental assembly. Unfortunately, most reconstructions are highly speculative mostly due to a deficit of high quality paleomagnetic data. For example, Evans and Pisarevsky (2008) argue that out of 600 published 1600-1200 Ma paleopoles, only eight satisfy all necessary reliability criteria. A few more recently reported paleopoles have improved the situation somewhat, but there are still not enough poles to construct a complete Mesoproterozoic Apparent Polar Wander Path (APWP) for any craton. However, the presence of pairs of precisely coeval paleopoles from continent pairs can provide a paleomagnetic test of the assumption that these two continents drifted together as parts of a larger supercontinent. Luckily there are a few such pairs between 1800 and 1000 Ma: there are reliable paleopoles from both Laurentia and Baltica at 1780-1740 Ma, 1480-1460 Ma and 1270-1260 Ma. Additionally there are coeval poles from Siberia and Laurentia at 1480-1460 Ma and even coeval fragments of APWPs for these two continents for ca. 1050-1000 Ma. These data suggest that these three continents (Laurentia, Baltica and Siberia) could all have been part of a single supercontinent between 1500 and 1270 Ma (Wingate et al., 2009). The proposed connection is supported by geological similarities between Archean crustal blocks and Proterozoic orogenic belts in two continents. However, additional paleomagnetic tests are required to verify this connection. The only possible way to do it at this stage is to involve some less reliable paleopoles. The Nordic Paleomagnetic Workshop in Lulea (2009) concluded that there are about 90 (64 of them – from Laurentia, Baltica, Siberia and Australia) Mesoproterozoic paleopoles of 'reasonable' quality and they can be used for the reconstruction of the Mesoproterozoic supercontinent. Most of these poles support the proposed Laurentia-Baltica-Siberia reconstruction. New 1420 Ma South American data permit a connection of Baltica and Amazonia at that time, but this connection had to be broken long before 1200 Ma. Paleopoles from India, Australia, Congo, North China and Kalahari cannot establish unequivocal positions of these blocks in the Mesoproterozoic supercontinent, but some alternative reconstructions are proposed and tested with geological data.

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MAGNETISM OF TILTED MIDDLE ORDOVICIAN CARBONATE SEQUENCE IN NORTHEASTERN ESTONIA

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The variably tilted Middle Ordovician (Kunda and Aseri regional stages, early Darriwilian) layered carbonate strata in NE Estonia (Baltica) were studied by mineralogical, palaeomagnetic, and rock magnetic methods in order to specify the post-sedimentational history of the area and to test the palaeomagnetic components for obtaining a better control over the Apparent Polar Wander Path of Baltica. The area under interest includes diaper-like features of the Lower Cambrian clay and upheavals of Ordovician carbonates. The genesis and timing of the upheavals have been associated with their lateral movements by a glacier (e.g. Jaansoon-Orviku 1926) and interpreted as ice marginal formation (Miidel et al. 1969). Based on the fact that the orientation of clay folds is generally to the east or northeast, and follows direction of tectonic fault zones in the region, Puura and Vaher (1997) suggested that the deformed structures may have tectonic heritage and are reworked later by the recent glacier.

The study is based on 204 oriented drill-core samples and three block samples that were collected from thirteen sites in eight locations. Most of the sites were of natural origin and consisted of strata that were tilted at a different degree with dips from 4 to 70°. Mineralogy was studied in thin sections by polarization microscope, X-ray diffractometry, and SEM. The magnetic measurements consisted of Lowrie (1990) test, temperature dependence of magnetic susceptibility, and hysteresis. Alternating field and thermal demagnetization were used to study the behaviour of remanent magnetization.

Two components of remanent magnetization were identified:

First, a southeasterly downwards directed component P (9 sites, Dref=141.7±11.8°, Iref=64.1±6.4°, k=40.1, α_{95}=8.2°) dates to Ordovician (pole P: Lat=19.8°N, Long=55.3°E). Mineralogical studies revealed that (Ti-)magnetite is responsible for the medium-coercivity component P. As Fe^{2+}-bearing minerals are rapidly oxidized when brought into contact with oxygen and not involved in transport of iron into the ocean (e.g. overview by Raiswell 2011); magnetite within the carbonates has likely been formed through post-depositional chemical reactions under locally reducing conditions and is thus linked to diagenesis and/or early dolomitization.

Second, a northeasterly downward directed high-coercivity and high unblocking temperature component S (2 sites, Dref=37.7°, Iref=57.5°) represents a Triassic (pole S: Lat=58.0°S, Long=322.7°E) remagnetization. The carrier of component S is hematite and by its mineralogical relationship with dolomite proves hematite post-dates the diagenetic dolomitization. Thus, hematite is most likely of chemical origin and indicates near-surface alteration by meteoric fluids (Plado et al. 2010).

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THE ODISSEY OF BALTICA

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Taking into account the venue of our Symposium, it is appropriate to pay special attention to Baltica as a building block of supercontinents and as one of the important subjects in the jigsaw of the Earth's lithosphere since the end of Paleoproterozoic.

Baltica: what's in the name? Baltica is usually referred to as a continent or a craton, with a certain uniqueness in its form and stable relations with other continents. But in fact, its history has shown several amalgamations and break-ups which have changed the shape of the block. Still, despite to additions and deletions, the Archean-Paleoproterozoic (cratonic) core of it persisted since the end of the Paleoproterozoic till now, and the name has sense.

The Northern margin. It is widely accepted that Baltica was a result of a welding-up of three smaller continental blocks – Fennoscandia, Sarmatia and Volgo-Uralia - which took place at 1800-1700 Ma (Bogdanova et al., 2008). But during the time when supercontinent Nuna was formed there was only a small chance that Baltica was then an individual continent. More probably, Fennoscandia was a part of Laurentian block; Sarmatia and Volgo-Uralia just joined it in the configuration of Nuna supercontinent. Both paleomagnetic data (Lubnina, 2009) and direct correlation of geological boundaries between the N-E Laurentia and Scandinavia (Hoffmann,1989) speak in favor of this point of view. The idea that Baltica broke apart from Laurentia and then docked at it again any time in the Meso- and Neoproterozoic (before the Ediacaran), needs a support in an existence of a suture zone and orogen of this age between these two continental blocks. But there is no such data. Moreover, the co-Rodinian Grenvillian and Sveconogvegian orogenies are correlated athwart the assumed boundary between Baltica and Laurentia, not along it. The real proofs that Baltica acquired its northern boundary and real character, were given only for the Ediacaran (Bogdanova et al. , 2009).

The Eastern margin. The history of this margin is documented at its best in the Southern Urals; important data are provided also by geology of the Timan Range (Puchkov, 2010, Puchkov et al., submitted, Krasnobaev et al., submitted). The idea that amalgamation of Baltica took place slightly after 1800 Ma is supported by the study of the relationships between the crystalline basement of Volgo-Uralia (Taratash complex) and the overlying sedimentary rocks of Kama-Belsk aulacogen that had a non-Uralian, NNW strike, subparallel to the grain of the crystalline basement. The volcanics close to the base of this sedimentary succession are dated recently at 1752±11 Ma (Krasnobaev et al., submitted). Definite data on a process of destruction of the eastern Baltica was acquired from the study of the Mashak Formation, which contains abundant basalt-rhyolite volcanics of a within-plate, rift type. The strike of the reconstructed rift is NNE, i.e. parallel to the Urals and transversal to the strike of the crystalline basement: a real indication of destruction of the latter. The rhyolites, situated close to the base of the formation, were reliably dated by U-Pb methods (IDTIMS, CA IDTIMS, SHRIMP) in three laboratories around the world on zircons, as 1380-1385 Ma. It was shown that volcanic rocks and intrusions of this age are developed at a vast territory of the Eastern Baltica, including the eastern part of the East-European platform and Timan Range. In the Southern Urals we see only very thick (more 15 km) shelf sediments, but no deep-water sediments. In the Timan, the Externides of Timanides are represented by both shallow-water and deep-water sediments, more than 1000 Ma in age and younger, substituted in the east by Internides with ophiolites and suprasubdustional complexes, indicating at the formation of a passive continental margin by this time. As it was suggested by Evans and Mitchell (2011), in the period of 1740-1260 Ma Laurentia, Baltica and Siberia kept tightly together. It permits to look for analogues of the Mashak event in these continents. The Mashak event can be correlated with coeval magmatic rocks in northeastern Greenland (Zig Zag Dal volcanics and Midsommersø sills) and Siberia (Chieress dyke and other dolerites). We suppose that the ca. 1380-1385 Ma Mashak event is a part of a single LIP (including equivalent magmatism in Siberia and NE Laurentia) and corresponds to an early breakup event of the Nuna supercontinent (Puchkov et al., submitted).

Baltica in the Ediacaran time. After a final breakup event of the Rodinia by 615 Ma (Bogdanova et al., 2009) Baltica became for a while an independent continent. The eastern margin of it was affected by the Timanian (Late Ediacaran) orogeny and strongly accreted because of it. It was time of Gondwana formation, and there is still a question: if Baltica was a part of a bigger continent, connected by the Cadomian and Timanian orogens. Until recently, there were many variants of a position of the Late Ediacaran pole of Baltica, but now the question becomes clarified (Bazhenov et al., 2012; Lubnina et al., submitted). According to newly-acquired pole positions of Baltica, the continent was situated in the low latitudes at this time, which makes the idea of an existence of Pannotia (Panterra) continent, bigger than Gondwana, more probable.

Baltica in the Phanerozoic time. Baltica, as well as the Northern Gondwana, experienced a new break-up in the Ordovician, and its outline changed again. In the Silurian, the development of the Caledonian orogeny made Baltica again a part of a bigger continent – Laurussia (Ziegler, 1999). Later on, and until now, Baltica never been a separate continent again. Its way from the low to middle latitudes, with all rotations and accretions, is known rather well (Svyazhina et al., 2002, 2003).

PALEOMAGNETIC AND ROCK MAGNETIC STUDIES ON THE 2.45-2.1 GA DIABASE DYKES OF KARELIA, EAST FINLAND - KEY FOR TESTING THE PROPOSED SUPERIA SUPERCRATON

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We present here paleomagnetic and rock magnetic data from Paleoproterozoic NW-, E- and NE-trending diabase dykes in eastern Finland, in the Karelian Province of the Fennoscandian Shield. The basement rocks consist of Archaean granitoids and greenstone belts that are partly covered by Paleoproterozoic Karelian formations. These are intersected by voluminous Paleoproterozoic mafic dyke swarms that extend from Finland to NW Russia. The area is mostly affected by the 1.9-1.8 Ga Svecofennian orogenic events, the majority of studied samples showing remagnetization of that age. However, part of the area is better preserved and primary Paleoproterozoic paleomagnetic data can be obtained.

In one of the now studied dykes with Sm-Nd model age of 2407 ± 35 Ma and εNd value +1.6 (Vuollo and Huhma, 2005) we obtained a moderately SE dipping component D. Its baked host migmatite gives a similar direction and has a virtual geomagnetic pole (VGP) Plat: -19°N, Plon: 266° (A_{95}: 4°). A similar magnetization has been earlier interpreted to represent the primary 2.45 Ga old magnetization in the mafic layered intrusions and associated dykes in the Karelia Province (e.g. Mertanen et al., 1999, 2006). Another magnetization component, component D', was obtained in the tonalitic baked basement rocks of one dyke, a similar component earlier separated in ca. 2300 Ma gabbro in the Karelian Province. This component yields the VGP (Plat: 15°, Plon: 266°, A_{95}: 5°) and its relative location compared to other Precambrian poles of Baltica suggests a magnetization age younger than 2.45 Ga but older than and 2.12 Ga. A third component E was obtained in 5 dykes and it yields a pole Plat: 37°N, Plon: 286°E, A_{95}: 13. Pole E on the apparent polar wander path of Baltica indicates an age of 2.3-2.06 Ga.

According to present and previous paleomagnetic data Karelia occupied equatorial latitudes at 2.5 Ga, moved on to the intermediate latitudes at 2.45 Ga, and back to the equator at about 2.3 Ga when it acquired the magnetization component D'. At 2.3-2.1 Ga Karelia was located on latitudes of 20-25°. The paleomagnetic data from the Karelia Province compared to similar aged paleomagnetic data from the Superior Province negates the tight Superia fit (Bleeker and Ernst, 2006; Bleeker, 2006), but allows a loose fit between 2.5-2.1 Ga.

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PALEOMAGNETIC STUDY OF THE MESOPROTEROZOIC SATAKUNTA DYKE SWARM, FINLAND, WITH IMPLICATIONS FOR A NORTHERN EUROPE – NORTH AMERICA (NENA) CONNECTION WITHIN NUNA SUPERCONTINENT

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Paleoproterozoic supercontinent Nuna (Columbia, Hudsonland) has been suggested by several studies. Many recent reconstructions of this supercontinent are based on assumption that the core of Nuna was formed by the united Baltica and Laurentia cratons forming the NENA (Northern Europe – North America) configuration that lasted from 1.8 Ga to at least 1.26 Ga. However, recent 1.6 Ga data from Greenland appear to challenge this fit (Halls et al., 2011). Our new data from the Mesoproterozoic (1565 Ma) diabase dyke swarm in Satakunta, western Finland, provides new paleomagnetic evidence to test the NENA configuration.

From the Satakunta dykes a dual-polarity, high-stability remanence component was obtained and it was confirmed to be primary by several baked contact tests. A suite of rock-magnetic analyses demonstrates that pseudo-single domain magnetite is the remanence carrier. The combined mean remanence direction for both polarities is D = 8.3°, I = 6.5° (α_{95} = 5.9°), yielding a new key paleomagnetic pole for Baltica at 32.7°N, 188.7°E (A_{95} = 4.2°). This pole fulfills six out of seven van der Voo factors. Based on the reconstruction by using the new Satakunta pole and the nearly coeval (1592 Ma) Western Channel Diabase pole from Laurentia (Irving, 1972; Hamilton and Buchan, 2010), the NENA fit existed at 1.57-1.59 Ga. Consequently, coeval paleomagnetic data coupled with correlations of geochronology and basement geology of Baltica and Laurentia validates the NENA fit at 1.77-1.75 Ga, 1.59-1.57 Ga, 1.46 Ga, and 1.27 Ga.

Using the same NENA reconstruction, the dual-polarity 1.63 Ga paleomagnetic poles from Greenland (Melville Bugt, Halls et al., 2011) and Finland (Sipoo, Mertanen and Pesonen, 1995) are offset by about 30°. However, when using the whole range of the fairly scattered data from individual sites, the NENA fit can be allowed. In Sipoo dykes, as well as in several other similar aged formations in Fennoscandia, the reversed polarity data are more scattered than normal polarity data, possibly due to transition of the Earth's magnetic field during remanence acquisition.

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THE METAMORPHIC AGE OF THE FORQUILHA ECLOGITE BELT IN THE NW BORBOREMA PROVINCE, NE BRAZIL

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During the Earth evolution, several phases of fragmentation and posteriorly agglutination of continental lithosphere are registered forming supercontinents. In the South American platform two breakup events occur before the Gondwanaland agglutination, result of fragmentation of possible Columbia supercontinent (~1.85 – 1.25 Ga) and Rodinia (1.05-0.75 Ga), around, respectively 1.8-1.6 Ga and 1.0 - 0.9 Ga. The Rodinia fragmentation and Gondwana assembly, are supported by several geological data in the South American (Fuck et al., 2008 and reference there in).

The assembly of West Gondwana *c.* 600 Ma was responsible by intense magmatism and tectonism, referred to as Brasiliano thermotectonic event in South America, that are well documented in the Borborema Province, NE Brazil. This province developed as a result of convergence of the West African–São Luís and São Francisco Cratons during the amalgamation of West Gondwana (Brito Neves *et al.* 2000). In the northwest portion of this Province occurs a retrograde eclogite belt, arranged in an N-S trend and measuring up to 6 km in width and more than 30 km in length, with metamafic and metasedimentary rocks (Figure 1). Previous studies have shown that the retrograded eclogites underwent pressure and temperature conditions greater than 17.3 kbar and 770ºC, respectively (Santos *et al.* 2009), and were probably derived from tholeiitic mafic protoliths as IAT and N-MORB type basalts (Amaral *et al.*, 2010). The LA-ICPMS U -Pb, Lu-Hf, and Sm-Nd isotopic data of metamafic rocks indicate a crystallization ages bettween 1547 to 1567, and a Hf model-ages (zircon grains) varying from 1.57 to 1.80 Ga with positive values of epsilon Hf from +7.46 to + 9.63 and Nd model ages ranging from 1.60 to 1. 79 Ga with positive epsilon Nd value of +4 that indicate a mantle source for this rocks. A consistent lower intercept show a Neoproterozoic age.

Migmatized sillimanite-garnet-biotite gneiss, kyanite-garnet-biotite gneiss and garnet bearing biotite gneiss represent the paragneisses sequence that host the retrograded eclogites. The metamorphic event recorded in the Forquilha belt was dated by U-Pb monazite and zircon and Lu-Hf zircon methods at the migmatite (leucosome and melanosome) and paragneiss. The source rock of the metasediments show a Paleoproterozoic provenance ages, while the metamorphic peak occur around 650 – 640 Ma. The Lu-Hf data from the same Neproterozoic zircon indicate a Paleoproterozoic mantle source with negative epsilon Hf . Thus, it is evident that the zircons grains that provided these ages were intensely reworked during the Neoproterozoic metamorphic event, here interpreted as the metamorphic peak result of the amalgamation of the West Gondwana in the NW Borborema Province.

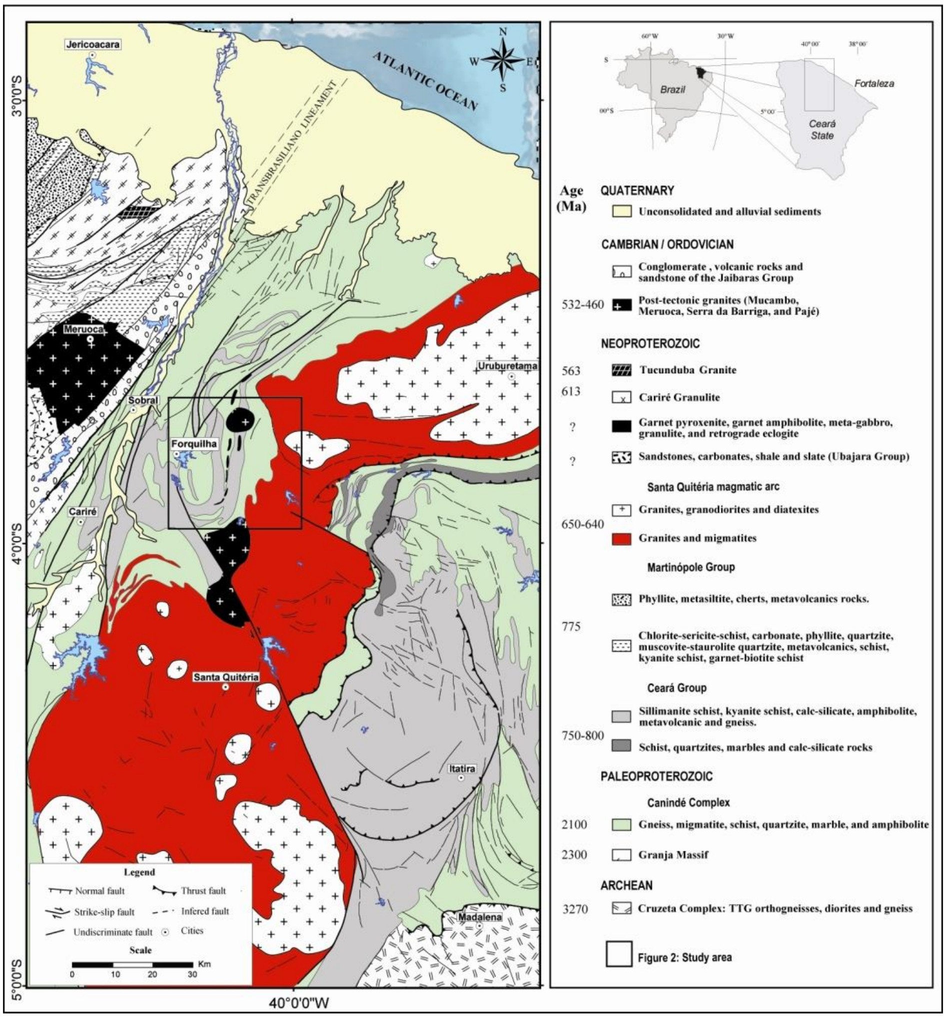

Figure 1. Simplified geological map showing the NW of the Borborema Province (Amaral et al., 2010)

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REFINING THE AUSTRALIAN NEOPROTEROZOIC APWP – INCLINATION CORRECTIONS

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It is now generally accepted that sediments commonly acquire compaction-related inclination shallowing of remanence directions (Bilardello and Kodama, 2010). Recognising this and making the necessary corrections has substantially improved the late Palaeozoic–early Mesozoic Pangaea fit (Domeier et al., 2012). Similar investigations are crucial in ascertaining the validity of low-latitude Neoproterozoic glaciations by determining any possible inclination shallowing in relevant glaciogenic and related red beds that are central to this low-latitude debate.

The anisotropy of hematite remanence acquisition and its role in assessing the fidelity of palaeolatitudes can be estimated by using several laboratory proxies.

The flattening factor, f, is usually defined as $\tan(I_D)/\tan(I_F)$, where I_D and I_F are the inclinations of the measured detrital remanence and the ancient inducing field, respectively. Therefore f is inversely related to the amount of correction, with $f = 1$ indicating faithful recording of the field direction. Anisotropy of induced remanence is often studied to estimate f. We have measured high-field anisotropy of isothermal remanence (hf-AIR; Kodama and Dekkers, 2004) using of superconducting magnet capable of generating a 12 T induction.

Anisotropy of thermal remanence (ATR) has also been examined by measurement at temperatures increased step-wise to allow the recognition of the onset of heat-induced chemical alteration. This procedure is labour intensive with over 60 thermal runs per specimen. However, the results vindicate the effort.

The elongation-inclination (E-I) method of Tauxe and Kent (2004) has also been applied. The E-I method compares the distribution of secular directional scatter with the observed latitudinal dependence for basaltic lava flows over the past 5 Ma.

Anisotropy of anhysteretic remanence (AAR) is useful for magnetite-bearing rocks but is not capable of dealing with the high magnetic coercivity of hematite.

ATR, hf-AIR and E-I allow corrections for inclination shallowing, which in turn permit more accurate estimates of palaeolatitudes for Cryogenian and Ediacaran red beds from the Flinders Ranges, South Australia.

For sediments from the Cryogenian and Ediacaran of the Flinders Ranges, South Australia, flattening factors have been found to vary from quite low values to high values (Table 1).

Table 1. Summary of anisotropy of remanence for late Neoproterozoic units, South Australia

Formation	hf-AIR		E-I		ATR	
	f	*sd*	*f*	*sd*	*F*	*sd*
Wonoka Fm	-	-	-	-	0.354	0.038
Brachina Fm	-	-	-	-	0.387	0.052
Nuccaleena Fm	0.98	0.02	0.74	n.a.	0.805	0.082
Elatina rhythmites	0.97	0.01	-	-	0.692	0.066
Elatina arenites	0.92	0.02	0.64	n.a.	0.738	0.088

f – flattening factor; *sd* – standard deviation; n.a. – not available

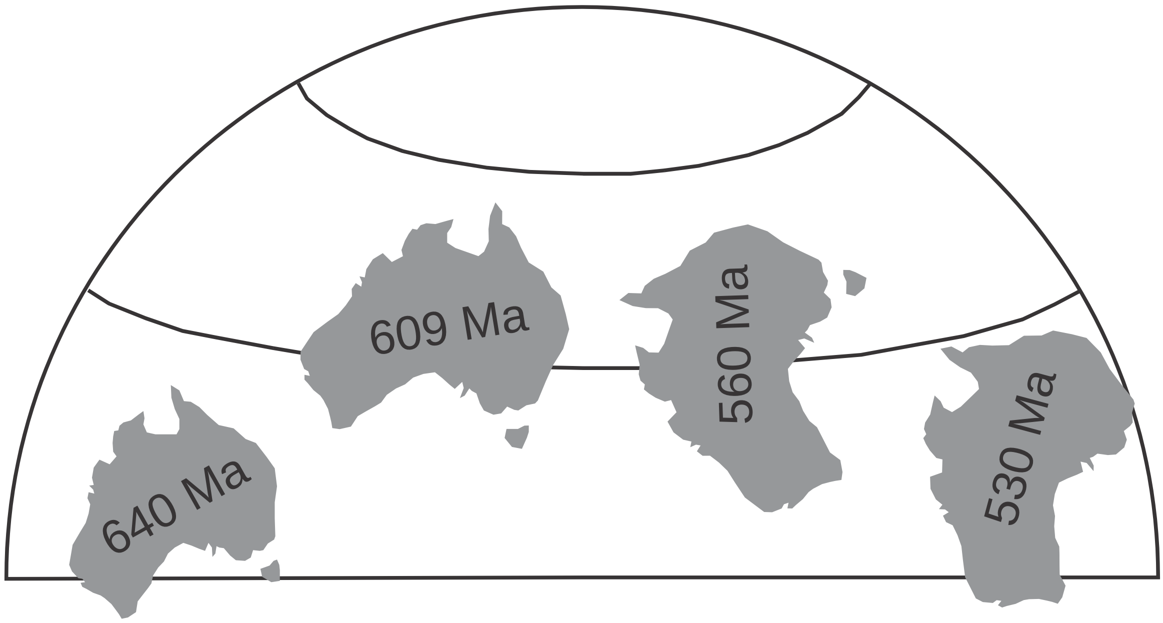

Figure 1. Palaeolatitudes of Australia from late Cryogenian to late Ediacaran times, after correcting argillite directions for inclination flattening determined from anisotropy of thermoremanence (ATR).

The hf-AIR *f* values for the late Cryogenian glaciogenic Elatina Formation and the post-glacial early Ediacaran Nuccaleena Formation are significantly higher than either the E-I or ATR values. Nevertheless, for the Elatina Formation arenites, which constitute the bulk of the Elatina data set, the inclination correction using *f* = 0.738 increases the palaeolatitude of the Elatina Formation from 6.5° to 8.8°. The inclination corrections for the Ediacaran argillaceous Brachina and Wonoka formations, using *f* = 0.35–0.38, are significantly greater than for the more arenaceous Elatina Formation, increasing their palaeolatitudes from ~12° to ~30°. Carbonates from the Nuccaleena Formation yielded *f* = 0.8, representing only a small palaeolatitude correction from 19° to 23°.

The results confirm that the late Cryogenian Elatina glaciation in South Australia (Williams et al., 2008, 2011) took place near the palaeoequator (Schmidt et al., 2009). However, the corrected palaeolatitudes for the Ediacaran argillaceous red beds change the shape of the Australian late Neoproterozoic APWP considerably, and recent suggestions of episodes of True Polar Wander (TPW) during the Ediacaran (Mitchell et al., 2011) must be reconsidered.

TPW does not yield a more simple or more satisfying interpretation of the data. Whereas TPW paths should be congruent for all continents, this does not appear to be the case for Australia and North America during the Ediacaran. Some Apparent Polar Wander must have occurred simultaneously, or exclusively. Without a hotspot reference frame, distinguishing between TPW and APW is fraught with ambiguity.

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SUPERCONTINENT STUDIES – IMPLICATIONS ON GOLD METALLOGENY

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Paleocontinental reconstructions and the recognition of supercontinents through time are essential for inter-block tracing of all geological and structural features of the lithosphere, including their deep mantle roots, and for providing a paleogeographic framework for assessing Earth's geodynamic evolution and climatic variations through time. Unfortunately, the state of understanding of pre-Pangaea reconstructions and their specific paleogeography is tentative at best. There is good evidence, based on the episodic nature of orogenic belts, that there have been several Precambrian supercontinents, specifically, in the late Archean (e.g., Kenorland, or perhaps three Supercratons; viz., Superia, Sclavia, Vaalbara), the late Paleoproterozoic (Nuna, also referred to as Columbia), and the Neoproterozoic (Rodinia). Beyond these general concepts, the exact reconstructions are poorly constrained. The high-quality paleomagnetic data and precise ages can resolve these issues unambiguously. Kerrich and Wyman (1990) suggested that late Archean magmatic-accretionary events in the Superior and Slave Provinces of Canada, Finland, Southern Africa, India and Western Australia, are all associated with orogenic gold deposits, likely corresponded to an early external supercontinent aggregation, and the secular distribution of all orogenic gold deposits, globally, were linked to episodes of accretionary tectonics. Accordingly, Archean and post-Archean orogenic load gold deposits have formed in a common convergent margin geodynamic settings. The lithologies, characteristic of the Archean (viz., komatiites, tonalites or Banded-Iron-formations) are unlikely to be the principal factors in the genesis of the Archean load gold deposits (Kerrich and Feng, 1992; Kerrich and Wyman, 1994).

Geologically, the greenstone belts which occupy a considerable portion of Peninsular India present the ideal setting for hosting load gold deposits since, similar greenstone terrains are hosting some of the large gold deposits all over the world. The geological setting in India is very similar to the North American Cordillera, the Yilgarn craton of Western Australia, the Slave province of the Canadian Shield and Kaapvaal and Rhodesian Archean cratons of Southern Africa. All these provinces/cratons/shields are known for number of gold producing mines and with very high success rate in gold exploration.

In the present study an attempt is being made to reconstruct the supercontinents by plotting the structural grains of Dharwar Craton and Slave Cratons, since they have geological similarities and U-Pb ages of mafic dyke swarms. According to French and Heaman (2010), these cratons were part of a former supercraton –Sclavia throughout the Archean, until they break up at 2.2 Ga. U-Pb dates of 2.52 Ga of the load gold mineralization of Dharwar craton obtained by Sharma et al. (2010) are very close to Re-Os isochron age of 2591 ± 37 Ma obtained by Ootes et al. (2011) for the gold mineralization in Yellowknife greenstone belt of Slave province. Furtherer, this reconstruction is substantiated by matching of late Archean structural grain of each craton, and the locations of 2.63-2.57 Ga plutons and the proximity of ancient terrains in both cratons.

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PALEOMAGNETISM OF THE PROTEROZOIC ULTRAMAFIC-MAFIC DYKES OF THE ONEGA STRUCTURE (PRELIMINARY RESULTS)

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An ultramafic-mafic dyke swarm of Palaeoproterozoic (Ludicovian) age is known to occur in the southwestern North Onega synclinorium. The dykes are best exposed northeast of Petrozavodsk. There, more than 30 NNE- to near-E-W-striking dykes, which range in thickness from tens of centimetres to 15 metres and have a length of up to tens of metres, were found over an area of about 2 km^2.

Picrobasaltic, olivinophyric, augitophyric and aphyric basalts and plagiophyric andesite basalts were identified on the basis of mineralogical composition. Host rocks are represented by basalts, picrobasalts, tuffs, tuffites and sediments of the Trans-Onega and Suisari suites. The metamorphism of the dyke rocks does not exceed greenschist facies.

Primary minerals are represented by augite, plagioclase (commonly albitized), vitreous mesostaisite, olivine (completely replaced by chlorite), chromite, titanomagnetite and exotic minerals such as jarlongite and hapkeite. So far, 9 out of 30 dykes have been sampled.

The demagnetization of the dyke samples has revealed two- to three-component magnetization. Two components were mainly revealed: one is associated with a modern magnetic field and the other (presumably a primary, old component) manifests itself in fields over 40 mT at temperatures over 350 degrees and is consistent approximately with an age of 1960 Ma.

The authors assume that the above dyke swarm is associated with the final phases of a Ludicovian plume, which was active in some areas of Fennoscandia such as the Onega, Pechenga and Kuolajärvi structures (Russia) and Northern Finland and Northern Norway.

A RUDIMENTARY EVENT HISTORY FOR MINERAL SYSTEMS IN FINLAND – LOCAL PHENOMENA OR RESPONSES TO GLOBAL EVENTS?

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Mineral exploration research has long been guided by empirical observations of spatial associations between metal endowment and geodynamic settings and secular variations through time (Groves et al., 2005; Maier and Groves, 2011). For example rifting and dispersal of continents generates thermal anomalies for volcanogenic and intrusive-related magmatic and hydrothermal systems, or defines the architecture of basins accommodating sediment-hosted hydrothermal deposits. Conversely, orogenic lode gold systems and high-level intrusive-related porphyry and epithermal systems are characteristic of convergent tectonic regimes. Rock magnetic studies are not only valuable in attempting to restore past configurations of mineralized terrains; petrophysical studies of density and susceptibility can be used to characterize and constraining the distribution and timing of mineralizing processes within individual terrains, through metamorphic and hydrothermal reactions that generate or obliterate magnetic minerals (Airo, 2005; Mertanen and Karell, 2012). This brief review presents several key events relating to mineral systems in Finland, their geodynamic context, to generate discussion as to whether they merely represent local phenomena, or correlate with global events.

A coherent understanding of the Archean evolution of the Fennoscandian Shield is emerging, but mineral endowment is relatively poor compared to Proterozoic terranes in Finland, and certainly when compared to the Yilgarn Craton and Superior Province. It is interesting to note that the virtually coeval komatiitic magmatism at 2.71 Ga at Kambalda and in the Abitibi is not recorded in Finland, eruptive ages being older. Similarly, orogenic gold mineralization, and the peak of crustal reworking, between 2.73-2.69 Ga is marginally older than the principal gold mineralization in the Yilgarn.

In Finland, there is a well-defined history of terrestrial magmatism through the Paleoproterozoic, commencing with bimodal volcanism and extensive layered intrusions between 2.45-2.39 Ga, containing the world-class Kemi chromite deposits and PGE mineralization; significant synemplacement or post-emplacement disruption and tilting of these complexes occurred prior to establishment of a stable terrestrial to shallow marine regime, with extensive 2.2 Ga mafic sills and supermature quartzite sequences. Disruption of this regime occurred progressively from 2.11 Ga, though isotopic age constraints are scarce, with mafic magmatism and a transition from carbonate platform to coarse-clastic turbidite and black shale basins. At 2.06 Ga, (coeval with the Bushveld Complex), further mafic intrusions were emplaced, as at Kevitsa, together with komatiites in Lapland (Hanski et al., 2001). The Talvivaara sediment-hosted Ni deposit, as well as the termination of the

Lomagundi-Jatuli C-isotope excursion (Melezhik et al., 2007) fall within this time interval, the upper constraint being deposition of a vast monotonous turbidite sequence following breakup and ophiolite formation at 1.95 Ga.

Svecofennian orogenic processes are characterized by Zn-rich synvolocanic mineralization at 1.91 Ga and a peak of both felsic and mafic plutonism, with the latter being prospective for Ni, around 1.88 Ga. Mesoproterozoic mineralizing events are in contrast rather trivial; compared with Australia, for example the period after 1.6 Ga containing Broken Hill, Olympic Dam, Mount Isa and the Lawn Hill zinc province, is only represented by rapakivi granite magmatism. No major post-Svecofennian basin formation is recorded, though thin onlap sequences up to Devonian age are preserved, attesting to prolonged cratonic stability; Neoproterozoic and Phanerozoic mineral potential is thus restricted to unconformity-uranium, regolith kaolin, kimberlitic pipes, and late Devonian alkaline intrusions.

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2.14 GA MORB-TYPE THOLEIITIC DYKES ON THE KARELIAN CRATON: POSSIBLE TIME-MARKER OF THE BREAKUP

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The numerous mafic dyke swarms emplaced between 2.32 and 1.97 Ga (Vuollo, Huhma, 2005) in the Karelian craton give important temporal and geodynamic information on the Paleoproterozoic breakup of Archean crust of the Baltic Shield. The time of final rifting episodes and Svecofennian and Kola ocean opening is still controversial. It is generally assumed to be of the age of Jormua ophiolite ca. 1.95 Ga or ca. 2.1-2.0 Ga, determined by changes in lithostratigrafic sequences (Laajoki et al., 2005; Lahtinen et al., 2008, Peltonen, 2005). Here we report new geochronological, isotopic and geochemical data on Paleoproterozoic MORB-type tholeiitic (MTT) dykes in the Karelian craton that could be the time-marker of the final stage of continental rifting and breakup.

The dykes of this type are found in Central Karelian, Vodlozero, and Kianta Archean terranes of the Karelian craton which differ in crustal age. The thickness of dykes (up to 100 m) and chilled contacts of parallel dykes (in the southern part of the Karelian craton) are indicative of rapid crustal extension. U-Pb zircon and Sm-Nd mineral isochron isotope dating of the MORB-type tholeiitic dykes gives an age of 2140 Ma.

MTT dykes of the Karelian craton are uniform in geochemical and isotopic characteristics regardless of the age of the host rock. They are low-Mg (up to 8.5 wt.% MgO) tholeiitic basalts with relatively low TiO_2 (up to 1.2% in chilled margins) and high FeO_{tot} (up to 16 %). The flat REE patterns with (La/Sm)n= 0.86 - 1.24, (Gd/Yb)n= 1.04 - 1.24, positive HFSE (e.g. Nb/Nb*= 1.03-1.57) anomalies, positive εNd values (+2.2-+3.0) and low Sr_0 (0.7013-0.7032) are characteristic for MTT dykes. These features show strong similarity of MTT dykes and N-MORB basalts. MTT dykes are slightly enriched in LILE and LREE relative to N-MORB that is well explained by crustal contamination. It is also emphasized that MTT dykes of the Karelian craton are similar in geochemistry with syn-breakup low-Ti basalts on Faroe Islands (NAIP, Søager, Holm, 2011) and LREE-depleted Djibutu basalts in Afar (Daoude et al., 2010).

According to the modeling results the crustal component in MTT dykes does not exceed 8.5 wt. %. The geochemical and Nd-Sr isotopic characteristics of MORB-type tholeiitic dykes of the Karelian craton record ca. 10% melting of depleted mantle in spinel stability field. Lateral uniformity of these characteristics within the Karelian craton suggests that primary melts of MTT dykes were originated from homogeneous shallow upper mantle source, possibly from asthenosphere mantle.

The occurrence of such conditions on the Karelian craton with thick Archean lithosphere assumes lithosphere thinning and rise of asthenosphere. These processes could be explained by two models: rise of a mantle plume or gravitational delamination of lithospheric root. The second assumption is in the better agreement with available data.

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REINFORCING THE PALEOMAGNETIC BACKBONE OF RODINIA: NEW CONSTRAINTS ON THE LATE MESOPROTEROZOIC KENEEWANAM TRACK

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The Keweenawan Rift of North America initiated ∼1109 million years ago and associated volcanism continued, albeit with hiatuses in different regions, until ∼1086 million years ago (Davis and Green, 1997) when volcanism ceased. The end of volcanic activity and active extension occurred before an ocean basin formed and the "failed" rift contains a thick intact sequence of rift volcanics and sedimentary rocks. The >20 million-year history of rifting makes the volcanics, intrusives and sedimentary rocks of the Keweenawan Rift very important archives of paleogeographic information for Laurentia and associated cratons as Rodinia continued to assemble in the late Mesoproterozoic. Paleomagnetic poles from rift-related rocks have led to an apparent polar wander path known as the "Logan Loop" for older than 1100 Ma high-latitude poles that then continues into the "Keweenawan Track" that is comprised of younger and progressively lower latitude poles. It is largely through comparison of paleomagnetic data from other cratons to this apparent polar wander path that geoscientists seek to develop and test reconstructions of the supercontinent Rodinia (e.g. Weil et al. (1998); Li et al. (2008); Evans (2009)). The central role of this path to paleogeographic reconstructions of Rodinia emphasizes the importance of understanding whether the changing pole position of Laurentia at this time is the result of large non-dipole contributions to the geomagnetic field (the hypothesis of Pesonen and Nevanlinna (1981)) or whether it is due to plate motion (the hypothesis implicitly favored in many reconstructions albeit oftentimes with stated uncertainties as a result of apparent reversal asymmetry). Furthermore, the central role of the Keweenawan Track to reconstructions of Rodinia motivates ongoing efforts to further constrain the apparent polar wander path in time and space.

We present ongoing research that expands the paleomagnetic record from Mamainse Point, Ontario to include 100 lava flows (adding to the data presented in Swanson-Hysell et al., 2009) and from the Osler Volcanic Group to include >50 flows. Together these data sets further support the interpretation that the transition from steep to shallow paleomagnetic inclinations in rocks from the rift is the result of progressive equatorward motion of Laurentia, rather than an artifact of large non-axial dipole contributions to the geomagnetic field. A new chemical abrasion TIMS U-Pb date from euhedral prismatic zircons of a crystal-rich tuff in the Mamainse Point stratigraphy anchors the succession in absolute time. This additional constraint on Keweenawan magnetostratigraphy furthers efforts to quantify the implied rapid rates of plate motion. In order to determine the range of rates permitted by the uncertainties associated with both the U-Pb dates and paleomagnetic poles, we apply a Monte Carlo simulation method. This approach identifies aspects of the current database where tighter constraints on pole position and age would significantly further understanding of the rapid changes in paleogeography that were ongoing in late Mesoproterozoic time.

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JUVENILE ACCRETION (2360-2330 Ma) IN THE SÃO FRANSISCO CRATON, AND IMPLICATIONS FOR THE COLUMBIA SUPERCONTINENT: U/Pb AGES, Sr-Nd-Hf AND GEOCHEMICAL CONSTRAINTS FROM PLUTONIC ROCKS OF THE MINEIRO BELT

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The Mineiro belt and the northward Itabuna-Salvador-Curaçá belt are distinct Paleoproterozoic orogenic segments that surround the Archean core of the São Francisco craton. From the tectonic point of view, the northern belt includes island-arc accretion with preserved portions of the accretionary prism and back-arc basins. It comprises acid, basic-ultrabasic intrusions related to a ca. 2.5 Ga rift, 2.4 Ga monzonites and gabbros of shoshonitic affinity, 2.2-2.1 Ga greenstone belts, alluvial to marine foreland basin strata (ca. 2.0 Ga) and late kinematic plutons (low K calc-alkaline granulites and peraluminous granites). The Mineiro belt evolved marginally to an old passive margin basin filled by the Minas Supergroup (<2.55 to 2.35 Ga) overlaid by foreland basin strata (2.0-1.9 Ga). The Minas sequence is restricted to the Quadrilátero Ferrifero and to a narrow N-NE zone toward the southwest which marks the tectonic front of the Mineiro belt against the Archean core. Granitoid rocks and mafic, calc-alkaline plutons with peak ages between 2.25-2.20 Ga and 2.12-2.08 Ga, along with coeval back arc assemblages are also characteristic of the Mineiro belt. The Paleoproterozoic tectonic framework also includes regional metamorphism and related faults, shear zones and thermal aureole rocks in dome structures across both belts. These features are also portrayed in the West Central African belt (of Eburnean age) by considering the early contiguous São Francisco/West Congo-North Gabon landmass. We present U-Pb zircon ages and Nd-Hf-Sr isotopic and geochemical data for the Resende Costa orthogneisse (Mineiro belt) which provide new insights on the Early Proterozoic crustal growth processes and address further inferences related to supercontinent reconstructions. These data also bracket the maximum depositional age of the Minas Basin, given the available U-Pb zircon detrital ages of the siliciclastic sequences in the Quadrilátero Ferrífero. The Resende Costa pluton crops out in the vicinity of Paleoproterozoic metavolcanic-sedimentary sequences, whilst it exhibits tectonic contact with the late kinematic Ritápolis batholith (2121 Ma). The gneissic rocks are slightly metaluminous to peraluminous, subalkaline, show varied SiO_2 (69 to 73wt.%) contents, and low K_2O and high- Na_2O +CaO ones. Chemically, they are compatible with high Al_2O_3 trondhjemites of volcanic arcs. They also show weak positive Eu/Eu* anomalies, low Rb (24 to 70ppm), Ba (500 to 1000ppm), Th (2.1 to 8.5ppm) contents, very high Sr/Y ratios (75 to 158) and variable LREE and low HREE patterns (Yb < 1.23 ppm). Two samples yield comparable U-Pb (LA-ICPMS) zircon crystallization ages (2358 ± 10 Ma and 2356 ± 12 Ma), while the zircon rims yield 2133 ± 32 Ma, interpreted as the age of metamorphism. The T_{DM} Sm/Nd model ages are between 2.35 – 2.50 Ga, whereas the $\varepsilon_{Nd(t)}$ values range from +1.2 to +3.0, $\varepsilon_{Sr(t)}$ from +10 to -6, and $\varepsilon_{Hf(t)}$ between -3 to +6. The coeval Ramos tonalitic gneiss gives U-Pb zircon age of 2331 ± 17 Ma, T_{DM} age of 2.4 Ga, $\varepsilon_{Nd\ (t)}$ +2.2, $\varepsilon_{Hf\ (t)}$ (-9/+9) and $\varepsilon_{Sr\ (t)}$ +40 values. The broad signature for these rocks implies to short crustal residence for the protholiths with minor contamination during the petrogenesis. The nearby Lagoa Dourada suite shows a similar nature, according to the reported age and composition which is consistent with Early Proterozoic accretion in an intra-oceanic tectonic setting with greenstone belts. This suite consists of tonalites and trondhjemites with U-Pb crystallization ages of 2356 +3/-2 Ma and 2350 ± 4 Ma, and $\varepsilon_{Nd(t)}$ values from +1.0 to +2.1 (T_{DM} = 2.4-2.5 Ga). Chemically, these rocks are metaluminous to slightly peraluminous, with low-Mg#, low-K_2O and high-CaO, and varied SiO_2 contents (~62 to 73wt.%). Trace element geochemistry displays low large-ion-lithophile element (LILE, i.e., Rb, Ba, and including the highly incompatible Th) and heavy REE (Yb<1.00ppm) content. The Lagoa Dourada suite also shows high-Sr/Y ratios (≥41 up to 81), high-$(La/Yb)_N$ ratios (≥12 up to 46), and positive Eu/Eu* anomalies, as similarly as the Resende Costa rocks, and probably derived from a tholeiitic metabasaltic source which had a short crustal residence time prior to melting, as supported by the Nd evidence. To conclude, a juvenile accretion belt of Siderian age (2.36-2.33 Ma) is first time defined in the Southern São Francisco craton. It is one trace element of the multi arc system that built up the Mineiro belt outboard the Archean margin (Minas Basin: ca. 2580-2350 Ma), correlating well with the northern Itabuna-Salvador-Curaçá belt which similarly commenced around 2.4 Ga, according to geologic backgrounds and isotopic inferences. At continental scale, the Paleoproterozoic scenario is comparable with other roghly contemporary tectonic provinces in South America and West Africa (e.g. Amazonia/São Luis/West Africa and Rio de la Plata cratons), Laurentia, Baltica, Siberia, Central Australia, North China and India. From the geodynamic perspective, this reflects an important change in Earth`s regime at the Archean-Proterozoic times, given by propagation of accretional and collisional arcs, following which global assembly took place between 2.0-1.9 Ga – the Columbia Supercontinent - as suggested by geologic correlations, age constraints and paleomagnetic evidences.

SUPERCONTINENTS, LIPS, KIMBERLITES AND THE DEEP MANTLE

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The formation and break-up of supercontinents is the most spectacular demonstration of the Earth's dynamic nature. During Earth history, individual continents merged into landmasses that spanned large portions of the globe. Supercontinent amalgamation caused crustal thickening and generated vast mountain belts, extensional collapse and exhumation of deep-seated, high-pressure rocks. The existence of a single, large landmass within a global ocean is postulated to have created unique climatic and atmospheric conditions. Pangea (the most-recent, best-documented supercontinent) achieved her climax near the Permo-Triassic boundary, coincident with the Earth's largest known biological extinction. The long-term shielding effect of this supercontinent over a large part of the underlying mantle, which protected the mantle from subduction and cooling, have been argued to have caused an increase in sub-Pangean deep mantle temperatures. This temperature increase and the resulting mantle flow pattern have further been linked to a Large Low Shear Velocity Province (LLSVP) below Pangea. Two antipodal LLSVPs at the core-mantle boundary (CMB) beneath Africa and Pacific are prominent features identified in all shear-wave tomographic models and coincide with surface geoid highs. Thin patches of ultra-low velocity zones have substantially stronger (10% or more) seismic velocity reduction than the LLSVPs (~3%). The two reservoirs may represent fertile or primordial mantle that could have remained largely isolated for most of the Earth's history.

The rupture of Pangea (starting in the Jurassic) was preceded by, and associated with widespread volcanic activity, much of which produced Large Igneous Provinces (LIPs), commonly viewed as caused by eruptions from major plume-heads risen from the CMB. We have demonstrated that the centres of most LIPs of the past 300 Myr, when restored to their eruption sites, lie radially above one or other of two narrow belts centered on the 1% slow shear wave velocity contour of the SMEAN tomography model at the CMB, coined the plume generation zones (PGZs). We also find that many active hotspot volcanoes and more than 80% of all kimberlites formed within a part of a continent that at the time of kimberlite eruption lay close to above the PGZs.

It was not until Wilson's classic 1965 paper "Did the Atlantic close and then re-open?" that plate tectonic processes were understood to have been operating before Pangea. Wilson's succession of rifting, crustal subsidence and ocean opening, subduction initiation and ocean closure, and finally continent-continent collision was coined the 'Wilson Cycle' by Kevin Burke. The 'Wilson Cycle' concept also spurred an intensive search for older supercontinents — As many as five supercontinents have now been proposed and there may be a periodicity of ~500 Myr for their formation. Since the 1990's, Precambrian reconstructions have consistently incorporated the vaguely-resolved

Supercontinent Rodinia, which formed at ~1100 Ma and disintegrated between 850-800 Ma. Fragmentation was contemporaneous with massive LIP volcanism and several dramatic continental glaciations whose postulated low latitude spawned the Neoproterozoic Snowball Earth hypothesis. However, the story of Rodinia is obscured because only the latitudes of a few of her continents are known for any given time.

LIPs and kimberlites have erupted since the Archean and may all have derived from the margins of LLSVPs. Whether the African and Pacific LLSVPs have remained the same throughout Earth's history is less certain, but if true, we can reposition continents much older than Pangea with the PGZ reconstruction method. Possible evidences that the shapes and the antipodal locations of the LLSVPs on the equator have been time-invariant for longer period than 300 Myr, and thus insensitive to the formation of Pangea, come from reconstructions of kimberlites. Using the 360 Ma Yakutsk (Siberia) and 510 Ma Kalkarindji (Australia) LIPs to calibrate global reconstruction in longitude we generated semi-absolute reconstructions for the entire early and middle Palaeozoic and plotted kimberlite distributions from the major kimberlite-bearing continents (Laurentia, Siberia and Gondwana). These reconstructions indicate that all kimberlites that erupted between 341 and 542 My lay, at their times of eruption, above the African (Siberia, Southern Africa) and Pacific (Laurentia, Australia) PGZs.

For the first time the new PGZ longitude method that places LIPs and kimberlites above the edges of the African and/or Pacific LLSVPs will be used to restore continent positions for Neoproterozoic time. If the resulting reconstructed continents and plate motion histories are consistent with Rodinian (although vague) geological records, the stability of LLSVPs for the past 1.1 Ga is perhaps a viable model.

RECENT ADVANCES IN PALEOMAGNETISM OF SOUTH AMERICA: RELEVANCE FOR PROTEROZOIC SUPERCONTINENTS

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The assembly and disruption of supercontinents is thought to have impacted the long-term evolution of different envelopes of the Earth throughout Precambrian times, from mantle convection dynamics to feedback mechanisms leading to the stepwise change in atmospheric oxygenation. But the timing, duration, the size and the paleogeographic configuration of Precambrian supercontinents is still a matter of discussion.

The South American platform comprises several cratonic units, some of them larger than 30,000 km^2, such as the Amazon, Rio de la Plata and São Francisco, which are bordered by Neoproterozoic to Cambrian fold belts. These cratons are usually represented as key pieces of different supercontinental assemblies (or in 'supercratons' *sensu* Bleeker, 2003), including the Atlantica, Columbia/Nuna, Rodinia and Godwana. Reconstructing the supercontinents jigsaw puzzles requires a multidisciplinary approach, including the study of large magmatic provinces (LIPs), geochronology, paleontology, metalogenetic provinces etc.; the ultimate quantitative paleogeographic test being essentially the paleomagnetism. In recent years, a large amount of geochronological data and several new paleomagnetic poles were obtained for the three major cratonic units of South America that allow us to depict more precisely their role in the making of Proterozoic supercontinents.

Previous reviews of the Precambrian paleomagnetic database including the South American cratons (e.g., Pesonen et al., 2003, Tohver et al. 2006) revealed a marked paucity of data for all cratonic units, specially for key paleomagnetic poles (i.e. well-dated remanent magnetization, with field-tests that attest the primary character of the magnetization). The new database that will be reported in the talk shows a remarkable increase in the number of key poles and also other lower quality poles that enable to reconstruct some sectors of the apparent polar wander paths (APWP) of the different cratonic units.

For the São Francisco Crato a new paleomagnetic pole at 342.1◦E,−0.5◦N(N= 12, A95 = 9.6◦) was obtained for 12 sites of high grade metamorphic rocks from the Archaean/Paleoproterozoic Jequié block for which an age of of 2035±4Ma was attributed on the basis of hornblende Ar-Ar dating. This pole does not overlap similar age poles from Rio de la Plata (Soca and Isla Mala granites, 2056±6Ma and 2074±6Ma, respectively) still unpublished (A. Rapalini, personal communication). It also differs from Guiana Shield, West Africa and Kalahari poles thus precluding the existence of the Atlantica supercraton (sensu Rogers and Santosh 2002). On the other hand, new geochronological data from Neoproterozoic dykes from Bahia State (see Evans et al., this Symposium) seems to reconcile again the São Francisco Craton paleomagnetic data with some Rodinian configurations.

The most important advance in the Precambrian paleomagnetic database concerns the Amazon Craton. Recent paleomagnetic studies, some of them still unpublished allows one to track the participation of the Amazon Craton in several supercontinent assemblies from 2.0 Ga up to the end of the Proterozoic era. Amazonia was definitely part of the Columbia Supercontinent as attested by 1.78-1.79 Ga key poles. This supercontinent also comprised Laurentia, Baltica, North China, and Amazonia, forming a long and continuous landmass, linked by Paleo- to Mesoproterozoic mobile belts. Paleomagnetic data for Amazonian (see Bispo-Santos et al. and D'Agrella-Filho et al., this Symposium) support a long-lived connection between Laurentia and Baltica at least until 1.26 Ga ago. However, new paleomagnetic poles from the Amazonia Craton suggest that Columbia was in fact ephemerous, indicating a changing configuration between Amazonia and Baltica between 1.78 and 1.44 Ma. At the end of the Mesoproterozoic, the Amazonian craton is associated with the Rodinia supercontinent based on its record of Grenvillian events with overlapping ages with similar orogenic belts in eastern Laurentia. But its relative position in Rodinia is still intensively debated Presently only four poles for the Amazonian craton are available for the 1,200-900 Ma interval. Based on these results a dynamic model for the Amazonian craton was envisaged, which considers its oblique collision with southern Laurentia, followed by strike-slip migration along the Grenville belts, but other models are paleomagnetically also possible. During Neoproterozoic and Crambrian times the Amazonian Craton collided with the São Francisco Craton forming the West Gondwana. The existence of the large Clymene ocean between Amazonian and Congo-São Francisco cratons, implies that these units were not together in a fixed position within Rodinia and were assembled after the Precambrian, along a Cambrian suture zone.

During the talk we will present the paleogeographic configurations of the different supercontinents and supercratons allowed by the new paleomagnetic data and also the geochronological and isotopic constraints on the timing of assembly and break-up of continental assemblies.

PALEOSECULAR VARIATION IN THE PRECAMBRIAN AND THE VALIDITY OF THE GEOCENTRIC AXIAL DIPOLE THEORY

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The GAD (Geocentric Axial Dipole) hypothesis has been regarded as the cornerstone of paleomagnetism since its very beginning. However, Precambrian observations of the paleosecular variation (PSV, the scatter of poles vs. paleolatitude) shows evidence for significant non-dipolar contributions to the field (Tauxe and Kodama, 2009).

Paleosecular variation (PSV) has been used to explain also the recent changes in the geomagnetic field. For this purpose, several models of the field variation, e.g. CALS3K (Korte et al., 2009), CALS7K (Korte and Constable, 2005) and GUFM1 (Jackson et al., 2000), have been developed. Each of these models can be used to reconstruct the geomagnetic field in terms of spherical harmonic coefficients at a given time in their validity period. Properties of this field can be compared with those of a different era, e.g. Precambrian, and this provides a way to understand the long-term evolution of the geomagnetic field.

In our approach, we used CALS3K.1 model with the spherical harmonic coefficients that describe the geomagnetic field during the past three thousand years. In addition to the dominating zonal terms (g_1^0, g_2^0, g_3^0), there were also notable non-zonal terms, such as g_1^1 and h_1^1. At A.D. 0, the model showed the axial quadrupole term to be 5.8 % and the axial octupole term 3.2 % of GAD. Non-axial quadrupolar and octupolar terms are less than 1 % of the strength of GAD, so the model is at a first approximation near GAD. Because the field has become much more asymmetric during the last 1000-1500 years, IGRF models are not good for this kind of modelling, nor are CALS3K and CALS7K after A.D. 500.

Our modelling is based on creating a synthetic dataset of virtual geomagnetic poles (VGPs) from CALS3K model with 250 years as a time interval. We separated the globe into 10-degree latitudinal bands. In each band, the latitude was kept fixed while the longitude of the sampling site was shifted at 10-degree intervals. The scatter of the resulting 36 VGPs (S parameter) was determined for each latitudinal band, and results were compared with the G-curve of PSV (scatter of poles vs. latitude, see McFadden and McElhinny, 1998). They separated the geomagnetic field into *dipolar* (asymmetric) and *quadrupolar* (symmetric) families. Only the dipolar family (e.g. axial dipole and octupole) accounts for the increasing scatter of VGPs with respect to latitude.

To link models to observations, we calculated the values of the S-parameter for the best entries in our Precambrian paleomagnetic database (Evans et al., 2012, this volume). In order to calculate the true between-site S-parameter (S_B), we first subtracted the within-site contribution (S_W) of the total (observed) S_T. The within-site S_T appeared to be small (≤2°) and independent of latitude. We observed a strong correspondence with the G-curve especially in shallow and intermediate latitudes. Our PSV-analysis suggest that the long-term geomagnetic field of the Precambrian must be very prominently of dipolar nature, with the non-dipolar terms contributing far less than 10 % of the total field content.

We have now evaluated the GAD hypothesis by using three independent methods: 1. inclination analysis, 2. reversal-asymmetry analysis and 3. PSV. When combined, the results strongly support the applicability of the GAD-model for the Precambrian as a whole.

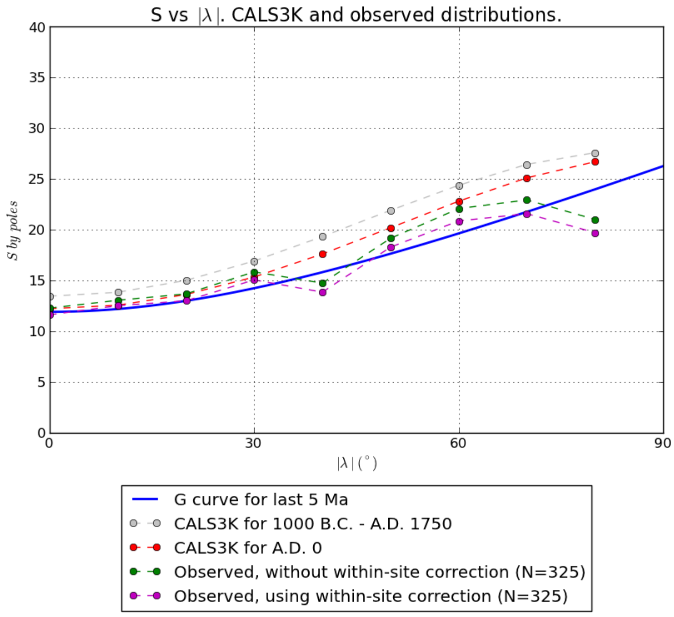

Figure 1. The observed dispersion of virtual geomagnetic poles (S-parameter) from Precambrian paleomagnetic observations. Uncorrected observations have a slightly higher scatter than data, which include the within-site scatter correction. The blue line shows the G-curve (McFadden and McElhinny, 1988).

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THE RELIABILITY OF THE GEOCENTRIC AXIAL DIPOLE MODEL AS EVALUATED FROM THE REVERSAL ASYMMETRY OF THE PRECAMBRIAN GEOMAGNETIC FIELD

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Since its beginning, the paleomagnetic method has laid on the assumption that the long-term average of the geomagnetic field is indistinguishable from a field generated by a geocentric axial dipole (GAD-hypothesis). This assumption holds true in the Paleozoic, but in the case of Precambrian, its applicability has been questioned.

The magnetic field of the Earth changes its polarity in irregular intervals (Clement, 2004). In the reversal event, declination on a given site is shifted by 180 degrees, whereas the inclination changes its sign, if the field follows the GAD hypothesis. In paleomagnetic sense, this means that the virtual geomagnetic poles calculated from both magnetic polarities would be equal. In the case where GAD is contaminated by a permanent axial (zonal) non-dipole terms the inclinations of N and R polarity units are not equal but reveal an asymmetry or the so called inclination anomaly (ΔI). These can be identified also on pole plots where the N and R poles plot onto a great circle, passing the sampling region.

The inclination anomaly, $|\Delta I|$, is very sensitive to small changes in axial quadrupolar and octupolar components. A strong inclination anomaly has been observed e.g. in results from late Precambrian Keweenawan rocks of the Lake Superior region (Nevanlinna and Pesonen, 1983), but the origin of this asymmetry is still disputed.

For studying the inclination asymmetry, we used the updated Precambrian paleomagnetic database collected by University of Helsinki, and Yale University (Pesonen et al., 2012, this volume). Out of the database, 123 entries with normal and reverse polarities from 11 continents were accepted for the final analysis. We note here that the terms normal (N) and reversed (R) must be applied to each craton separately, since their definition (due to lack of detailed APW paths) is arbitrary in global sense. Using 10-degree latitudinal bins, the inclination anomaly was calculated.

Results show that the inclination anomaly has no correlation with age, but a moderate correlation with the paleolatitude. Observations are best explained by a geomagnetic field model with an axial dipole (GAD), a quadrupole (3 % of the strength of the GAD) and an axial octupole (6 % of GAD) (Fig. 1).

Our observations and the best-fit model are in good accordance with the results obtained from inclination frequency analysis (Veikkolainen et al., 2012, this volume). Methods are independent of

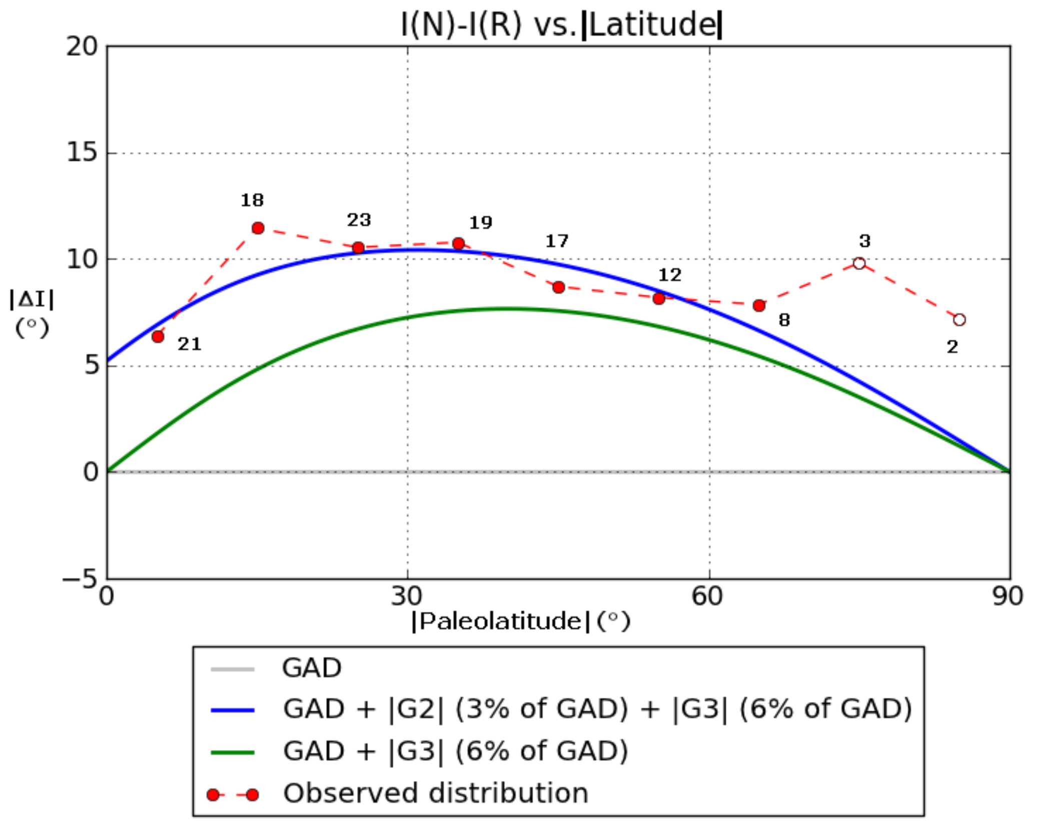

Figure 1. Results from an asymmetry analysis using igneous and regional metamorphic rocks. Here the inclination anomaly |ΔI| is plotted against the paleolatitude. Altogether 123 polarity pairs from 11 continents have been used. The two highest-latitude points are suspicious due to a low amount of data. Only results with Voo-grading (Van der Voo, 1993) for both polarities > 3 were accepted.

one another, but they together show strong evidence for the validity of the GAD hypothesis during the Precambrian.

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THE PRECAMBRIAN GEOMAGNETIC FIELD HAS NO PROMINENT LOW-INCLINATION BIAS

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Paleomagnetic measurements from igneous and metamorphic rocks prove the existence of the internal geomagnetic field since 3.5 billion years ago. However, it has been disputed whether the Geocentric Axial Dipole Model (GAD) can be used to describe the temporal mean of the Earth's magnetic field during the Precambrian (Kent and Smethurst, 1998) (Tauxe and Kodama, 2009).

There are numerous ways to test the validity of the GAD hypothesis. We have used the inclination frequency analysis (Evans, 1976), which was applied to the global paleomagnetic database collected by University of Helsinki and Yale University, USA (Evans et al., 2012, this volume). There were 3186 observations from 29 continents altogether. Since inclination data from sediments is strongly distorted towards low values, only igneous and metamorphic rocks were taken into account. The reliability of observations was estimated using the modified Voo-grading (Van der Voo, 1993), where the scale was from zero to six. The seventh grade is irrelevant for the Precambrian.

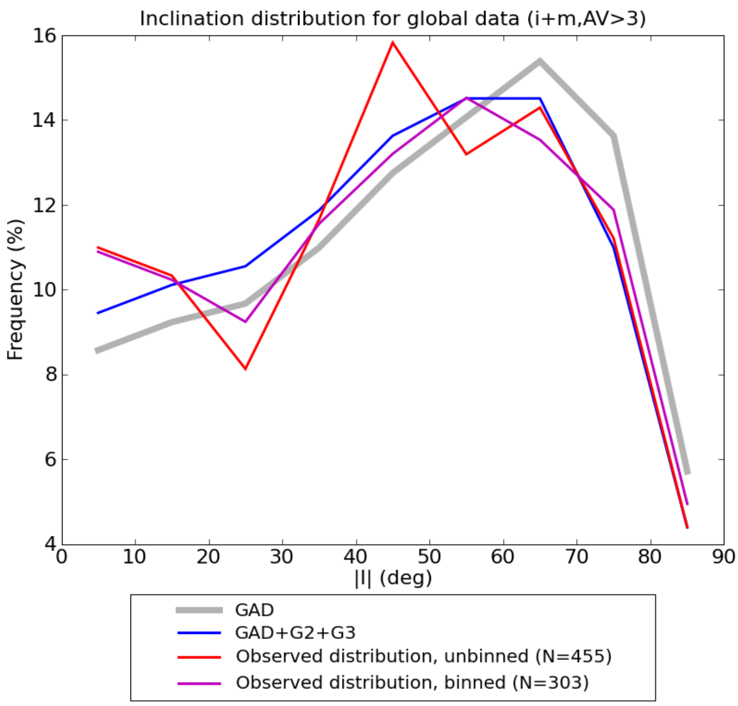

Figure 1. Comparison of binned and unbinned observations for filtered global Precambrian data from igneous and regional metamorphic rocks. In the best fit, quadrupole (G2) is 0 % and octupole (G3) is 5 % of GAD. Binning reduces concentrations of observations from same rock units. AV stands for the modified Voo-grading.

The geomagnetic field can be described as a combination of spherical harmonic terms. As each set of them generates a distinct inclination distribution, combinations of axial dipolar, quadrupolar and octupolar fields have been used for calculating theoretical models. The best-fit model can be found by comparing these theoretical observations with the observed distribution, with the aid of chi-square testing. The sign of inclination can be neglected, since magnetic polarities for the Precambrian are mostly uncertain.

We have proved that the geomagnetic field of the Precambrian is not far from the field predicted by the GAD model. Results from the analysis support the existence of a small octupolar (ca. 5-6 % of GAD) component and no quadrupole at all. The deviation from the GAD is smallest for the highest-quality observations, especially so called key poles.

Despite these results, we cannot be sure of the validity of the GAD model on the basis of inclination frequency method only. However, we have further studied the hypothesis by using the paleosecular variation analysis (Veikkolainen et al., 2012[a], this volume) and asymmetries of the reversals of the field (Veikkolainen et al., 2012[b], this volume).

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PALEOMAGNETISM OF DEVONIAN DYKES FROM THE NORTHERN KOLA PENINSULA AND ITS IMPLICATIONS TO THE EVOLUTION OF PRECAMBRIAN SUPERCONTINENTS

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Middle-Late Devonian dykes of alkalic to normal composition are common in many parts of the Kola Peninsula. We sampled dolerite dykes along the northern coast of the Peninsula and subjected the collection to stepwise thermal and af demagnetization. The following remanences are identified in these dykes:

a) a low-temperature component that is aligned along the present-day field and is likely of viscous origin;

b) a well defined dual-polarity intermediate-temperature component with steep eastward directions that accounts for a main part of the NRM and often decays to the origin on orthogonal plots;

c) a dual-polarity high-temperature component with shallow inclinations and ENE declinations of presumed primary origin.

Our presentation will be focused on interpretation of the intermediate-temperature component and its implications to the apparent polar wander path of Baltica and positioning of this craton within the Rodinia supercontinent.

BALTICA IN THE NEOPROTEROZOIC: NEW PALEOMAGNETIC DATA FROM THE VARANGER SEDIMENTS, NORTHERN NORWAY

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The thick sedimentary sequences of the Varanger peninsula in Arctic Norway span a time interval from the Cryogenian through Ediacaran to Early Cambrian, and as such provide a potential archive for tracking the movements of Baltica through a period characterized by Rodinia Breakup, possible global glaciations and the appearance and diversification of complex life forms. Unfortunately, good paleomagnetic data from Baltica are at present largely missing through the Cryogenian. Ediacaran studies are more abundant, but data from both Laurentia and Baltica seemingly yield internally inconsistent results, fuelling debates about True Polar Wander and/or possible equatorial geomagnetic dipole fields (Abrajevitch and Van der Voo 2010).

In an effort to shed more light over the movements of Baltica through this period, a new paleomagnetic study of the Varanger sediments has been undertaken. So far a total of 31 independent sites (359 specimens) have been studied, with the majority (26 sites) in the Ediacaran part of the sequence.

Three sites (30 specimens) from red sandstones and siltstones in the Cryogenian Fugleberget formation yield high stability and directionally consistent remanence components which suggest equatorial latitudes, although the exact age of this formation is not well constrained.

The most paleomagnetically robust result is obtained from sand- and siltstones of the Nyborg formation. This formation stratigraphically overlies the glacial Smalfjord formation, which is widely taken to represent the Marinoan "Snowball Earth" event. A total of 13 sites (167 specimens) yield a dual polarity magnetization, as well as improved grouping after tectonic correction from fold tests undertaken at several sites. The mean direction suggests a latitude of about 30°S, thus giving support to the notion that the glaciation responsible for the Smalfjord tillite must have been extensive. A previous study of the same formation by Torsvik et al. (1995) yielded broadly similar results.

In contrast to the Nyborg results, the overlying Mortensnes tillite (3 sites/33 specimens) and siltstones of the Stahpogiedde formation (10 sites/114 specimens) yield consistently steep down-pointing magnetizations, indicating near polar latitudes. However, these results should be viewed with some caution, since all sites have the same polarity and one of the Stahpogieddi localities yields a negative fold test. We note however, that the direction is inconsistent with a Caledonian remagnetization, and tentatively attribute the magnetization age to the D1 deformation phase of Herrevold et al (2009), which is believed to have occurred at ca. 560 Ma on the basis of RB/Sr illite dating (Ghorokov et al. 2001).

Taken at face value (i.e. disregarding the possibility of an equatorial dipole fields or a young remagnetization) the above results collectively suggest that Baltica moved from equatorial latitudes near the time of initial Rodinia breakup (ca. 750 Ma?) to moderate southerly latitudes just after the Marinoan glaciation, before moving to high southerly latitudes in the latest part of the Ediacaran. It is hoped that additional sampling to be undertaken in the older (Cyrogenian) parts of the sedimentary sequence will further elucidate this picture.

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U-PB GEOCHRONOLOGY OF DYKE AND SILL SWARMS OF THE WEST AFRICAN CRATON (ANTI-ATLAS INLIERS): POSSIBLE LINKS TO BREAK-UP OF PRECAMBRIAN SUPERCONTINENTS

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Remarkable mafic dyke and sill swarms (plumbing system of Large Igneous Provinces, LIPs) have been recognized in most inliers in the Anti-Atlas of southern Morocco. Only a few of these have been dated by modern geochronological techniques and most remain undated. On the basis of more recent geochronology (our new data combined with the data from the literature), the Precambrian mafic magmatism in the Anti-Atlas is represented by at least seven generations of dykes: (i) tholeiitic dykes of Paleoproterozoic age. Dykes in the Tagragra of Tata and Zenaga inliers have been dated at 2040 ± 6 Ma and at 2040 ± 2 Ma using the SHRIMP, ID-TIMS U-Pb methods on zircons (Walsh et al., 2002; Kouyaté et al., 2012); (ii) a microgranite from the Tafeltast-Kerdous inlier, which is cartographically and structurally associated with the mafic dykes in this inlier and to those in the Tagragra of Akka inlier, has been dated at 1760 ± 3 Ma using the ID-TIMS U-Pb methods on zircons (Gasquet et al., 2004). Our results (Youbi, Söderlund, Ernst et al., unpublished data) confirm the existence of this magmatic event not only in the Tagragra of Akka-Tafeltast Kerdous region but also in others Inliers (ca. 1758 Ma, Tagragra of Akka inlier; 1741 ± 10 Ma, Tafeltast-Kerdous inlier; 1747 ± 4 Ma, Iguerda-Taïfast and 1734 ± 5 Ma, Zenaga inlier; (ID-TIMS U-Pb method on baddeleyite and zircon) (iii) ages of 1656 ± 9 Ma, ca. 1655 Ma and 1654 ± 16 Ma (ID-TIMS U-Pb method on baddeleyite) were also obtained from the dyke and sill swarms of Zenaga and Agadir Melloul inliers (Kouyaté et al., 2012); (iv) two doleritic dykes from the Bas-Drâa inlier yield matching emplacement ages of 1384 ± 6 Ma and 1380 ± 9 Ma (ID-TIMS U-Pb baddeleyite; El Bahat et al., 2012); (v) approximate U-Pb ages of 885 Ma (U-Pb ID-TIMS U-Pb baddeleyite and zircon) for two dykes in the Iguerda-Taïfast and Zenaga inliers provide the timing for a NE trending swarm (Kouyaté et al., 2012);

(vi) Cryogenian dykes with tholeiitic and alkaline affinities, are coeval with the opening of back-arc oceanic basin in the Central Anti-Atlas (Clauer et al., 1982). U-Pb ages of 761 ± 2 Ma (ID-TIMS U-Pb method on zircon) have been obtained using zircons from plagiogranites associated with the Siroua ophiolites (Samson et al., 2004); (vii) post Pan-African mafic dykes, including those that crosscut the Taourgha granite, dated at 575 ± 4 Ma (ID-TIMS U-Pb method on zircon, Aït Malek et al., 1998) using samples from the Bas Drâa inlier. They may represent the feeder dykes of the volcanic successions of the Ouarzazate Group which is a part of the so called the Central Iapetus Magmatic Province (CIMP). The dated dyke and sill swarms of the Anti-Atlas inliers yield constraints on the reconstruction of the poorly constrained Columbia (Nuna), Rodinia and Pannotia supercontinents.

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