FIFTH INTERNATIONAL DYKE CONFERENCE

Abstracts and Programme

31 July - 3 August 2005, Pohtimolampi Wilderness Hotel - Polar Circle - Rovaniemi - Finland

FIFTH INTERNATIONAL DYKE CONFERENCE

"Dyke swarms - time markers of crustal evolution"

Pohtimolampi Wilderness Hotel -
Polar Circle - Rovaniemi - Finland
31 June – 3 August 2005

ABSTRACTS AND PROGRAMME

edited by

Jouni Vuollo
Geological Survey of Finland
P.O. Box 77, FIN-96101 Rovaniemi

Satu Mertanen
Geological Survey of Finland
P.O. Box 96, FIN-02151 Espoo

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Welcome from the Organising Committee

Welcome to Rovaniemi!

We are very pleased to host you here as a participant of the Fifth International Dyke Conference (IDC-5). The conference will bring together specialists in volcanology, tectonics, structural geology, petrology, geochemistry, geochronology, and geophysics to present progress made in the last years in various subjects related to dykes and other sheeted intrusions. An important part of the meeting are the pre- and post-conference excursions to the southern and eastern Finland and to the Kola Peninsula, Russia.

The meeting and the field excursions were made possible by the financial support of several organizations including Academy of Finland, Geological Survey of Finland, Universities of Oulu, Helsinki and Turku, European Diamonds PLC, Scandinavian Gold Limited and Kiviteollisuusliitto. Their support is gratefully acknowledged.

We wish you a pleasant stay in the field and in Rovaniemi, Arctic Circle.

Jouni Vuollo and Satu Mertanen

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STONE FROM FINLAND

PROGRAMME

Time		Monday	Tuesday	Wednesday
08:30 - 08:50		Opening	Patchett	
08:50 - 09:10		Ernst		De Oliveira Chaves
09:10 - 09:30			Graham	Coutinho
09:30 - 09:50		Vuollo	Huhma	Srivastava
09:50 - 10:10		Head	Hanski	Klausen
10:10 - 10:30		Break	Break	Break
10:30 - 10:50		Bleeker	Söderlund	Leat
10:50 - 11:10			Rämö	Romu
11:10 - 11:30		Elming	Luttinen	Riley
11:30 - 11:50		Pesonen	Eklund	Curtis
11:50 - 12:10		Piispa	Peng	End of Conference
12:10 - 13:20		Lunch	Lunch	Lunch
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13:40 - 14:00			Maurice	
14:00 - 14:20		Lefort	Teixeira	
14:20 - 14:40		Obst	De Oliveira Chaves	
14:40 - 15:00		Weinberger	Soesoo	
15:00 - 15:20		Break	Break	
15:20 - 15:40		Elming	Arzmastsev	
15:40 - 16:00		Mertanen	Shebanov	
16:00 - 16:20		Salminen	Alaabed	
16:20 - 16:40		Korhonen		
16.40 - 17:00		Lyakhovsky		
18:00 - 19:00	Registration			
19:00	Ice breaker party	Reception	Symposium Dinner	
	Hotel Pohtimo	Alaruokanen House - Rovaniemi	Hotel Pohtimo	

TALKS

MONDAY, 1 August 2005

08:40- 08:50 ***Lauri Pesonen***
Opening of the Conference

Chairperson: Lauri Pesonen

GIS databases

08:50- 09:30 ***Ernst R.E. & Buchan K.L.***
Dyke swarms and the Global Large Igneous Province (LIP) Atlas Project
09:30-09:50 ***Vuollo J. & Salmirinne H.***
Fennoscandian dyke swarms CD and map

Dyke swarms of planetary bodies

09:50-10:10 ***Head J.W. & Wilson L.***
Earth and Planetary Dike Emplacement: Insights into Geological Processes and Planetary History

Chairperson: Henry Halls

Dyke swarms and assembly of continents

10:30-11:10 ***Bleeker W.***
Mafic dyke swarms - the key unlocking Earth's paleogeographic record back to 2.5 Ga
11:10-11:30 ***Elming S.-Å.***
Basic dykes and dyke swarms in central and northern Sweden and the plate tectonic evolution of Fennoscandia: palaeomagnetic and Ar^{39}/Ar^{40} studies
11:30-11:50 ***Donadini F., Pesonen L.J., Korhonen K., Harlan S. & Deutsch A.***
New paleomagnetic, petrophysical and paleointensity results from the Gila County diabases, Central Arizona
11:50-12:10 ***Piispa E.J., Pesonen L.J. & Luttinen A.V.***
Antarctica - Kalahari reconstruction at 180 Ma – new paleomagnetic data

Chairperson: Satu Mertanen

Geophysics

13:20-14.00 ***Halls H.C.***
Dyke swarms and continental deformation
14:00-14:20 ***Lefort J.-P., Aïfa T. & Hervé F.***
New criteria to recognize the azimuth and the dip of a subduction just looking at the AMS data across its associated mafic dyke swarm. A 3 D geophysical and structural approach.
14:20-14:40 ***Obst K., Owens W.H., Hutton D.W. & Nowaczyk N.***
Magmatic flow in Permo-Carboniferous dolerite dykes of southern Sweden
14:40-15:00 ***Levi T., Weinberger R., Aïfa T., Eyal Y. & Marco S.***
Earthquake-induced clastic dikes detected by anisotropy of magnetic susceptibility

Chairperson: Sten-Åke Elming

15:20-15:40 ***Elming S.-Å. & Kravchenko S.***
A palaeomagnetic study of Mesoproterozoic basic dykes from the Ukrainian Shield and the amalgamation of the shield with Fennoscandia

15:40-16.00 ***Mertanen S.***
Paleo- and Mesoproterozoic dyke swarms at Lake Ladoga area, NW Russia – paleomagnetic studies

16:00-16:20 ***Salminen J. & Pesonen L.J.***
Preliminary paleomagnetic, petrophysical and rock magnetic data from Valaam sill, Lake Ladoga, Russian Karelia

16:20-16:40 ***Korhonen J.V.***
Pudasjärvi mafic dyke; geophysical and petrophysical interpretation

16:40-17:00 ***Lyakhovsky V.***
Propagation of pressure-driven fractures with implication to dike-induced seismicity

TUESDAY, 2 August 2005

Chairperson: Tapani Rämö

Isotope studies

08:30-09:10 ***Patchett P.J. & Söderlund U.L.***
Chemistry and isotopes in Precambrian mafic dikes: are they important samples of lithospheric or asthenospheric mantle?

09:10-09:30 ***Graham S., Andersen T. & de Haas G.-J.***
Lu-Hf and U-Pb of zircon from the Jomasknutene Gabbro, Bamble Area, southern Norway

9:30-9:50 ***Huhma H., Hanski E. & Vuollo J.I.***
Sm-Nd isotopes in Paleoproterozoic mafic rocks in Finland - evidence for rifting of Archean lithosphere and mantle sources

9:50-10:10 ***Hanski E., Huhma H. & Vuollo J.I.***
Sims zircons ages and Nd isotope systematics of the 2.22 Ga mafic intrusions in Northern and Eastern Finland

Chairperson: Hannu Huhma

10:30-10:50 ***Söderlund U., Isachsen C.E., Bylund G., Heaman L.M., Patchett P.J., Vervoort J.D. & Andersson U.B.***
Baddeleyite U-Pb dates of Meso- and Neoproterozoic mafic dykes and sills in the Baltic Shield

10:50-11:10 ***Rämö O.T., Mänttäri I., Kohonen J., Upton B.G.J., Luttinen A.V., Lindqvist V., Lobaev V., Cuney M. & Sviridenko L.P.***
Mesoproterozoic CFB magmatism in the Lake Ladoga basin, Russian Karelia

11:10-11:30 ***Luttinen A. & Kosunen P.***
The Kopparnäs basalt dyke reveals a hotspot source for the 1.64 Ga bimodal rapakivi association of southern Finland?

11:30-11:50 ***Eklund O., Fröjdö S. & Andersson U.B.***
The bimodal high-alumina basalt - A-type granite Korsö Dyke, SW Finland

11:50-12:10 ***Peng P.***
1.8 Ga Mafic Dyke Swarms of Central North China Craton and Continental Break-up

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Petrology and geochemistry

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Increasing enriched mantle component with time in Proterozoic mafic dyke swarms of the Ungava Peninsula, Canada

14:00-14:20 ***Teixeira W., Bettencourt J.S. & Rizzotto G.J.***
Asthenospheric signature in the Mesoproterozoic mantle below the SW Amazonian Craton: inferences from Nd-Sr compositions of mafic dikes and tectonic setting

14:20-14:40 ***De Oliveira Chaves A. & Correia Neves J.M.***
Precambrian evolution of the garnet lherzolite mantle beneath southern São Francisco Craton (Brazil) as revealed by Zr/Y ratios of mafic dyke swarms

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Chairperson: Eero Hanski

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Dyke swarms of the northeastern Fennoscandian Shield: a key for Paleozoic magmas emplacement

15:40-16.00 ***Shebanov A.D. & Eklund O.***
Lamprophyres in north Ladoga region and eastern Finland, evience of mantle enrichment at 1.8 Ga

Ophiolites

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Chairperson: Wilson Teixeira

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Mafic dyke swarms from Southeastern Brazil

09:10-09:30 ***Coutinho J.M.***
Dyke swarms of the Paraná triple junction

09:30-09:50 ***Srivastava R.***
Diverse Precambrian mafic dyke swarms, Bastar craton, Central India: evidence of a heterogeneous mantle source

09:50-10:10 ***Klausen M.B., Kramer J., Yao Y., Wilson A.H. & Chunnett G.***
Dyke swarms in the eastern Tibetan Plateau (Sichuan Province, China)

Chairperson: Richard Ernst

Dyke swarms of Antarctica

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10:50-11:10 ***Romu K.R.I. & Luttinen A.V.***
Kjakebeinet 159 Ma lamproites and their inclusions

11:10-11:30 ***Riley T. R., Leat P.T., Curtis M.L., Millar I.L. & Fazel A.***
Early-Middle Jurassic Mafic Dykes from Western Dronning Maud Land (Antarctica): Identifying Mantle Sources in the Karoo Large Igneous Province

11:30-11:50 ***Curtis M.L., Owens W.H., Riley T.R. & Leat P.T.***
The form, distribution and anisotropy of magnetic susceptibility of Lower Jurassic dykes in H.U. Sverdrupfjella, Dronning Maud Land, Antarctica. Implications for dyke swarm emplacement

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Development of parallel dike swarms and cone sheets controlled by the change of magma supply rate: dike swarms of the Miocene Otoge igneous complex, central Japan

Greiling R.O., Grimmer J. C., de Wall H. & Björk L.
Mesoproterozoic dyke swarms in central Scandinavia, their distribution, Caledonian overprint and geochemistry

Klausen M.B., Marsh J.S. & Watkeys M.K.
Correlating dyke generations to associated lava formations in the northern Lebombo monocline, Karoo large igneous province, South Africa

Munteanu M., Balogh K. & Kasper H.U.
East-Carpathian mafic dikes – indicators for post-Variscan crustal extension

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Söderlund U., Hellström F.A., Lundqvist I. & Patchett P.J.
U-Pb, Sm-Nd, Lu-Hf chronology of a Mesoproterozoic meta-dolerite suite in SW Sweden – the use of Hf isotopes for P-T-t constraints during metamorphism

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Intrusion types of the mantle sequence of the northern Semail ophiolite (UAE Section)

Sulaiman Alaabed

U.A.E. University, Geology, PO Box 17551, Al'Ain, U.A.E.

The mantle sequence of the Semail ophiolite represents an oceanic upper mantle tectonic peridotites of mainly harzburgites with little lherzolites and various types of intrusions. Three categories of intrusions have been recognized so far in the UAE upper mantle (Dibba-Masafi section). The ultramafic group that includes dunites, chromitites and pyroxenites, the granitic intrusions, and carbonate veins. Occurrences of these intrusions are explicit and ubiquitous, but their distribution throughout the sequence is not consistency. Pyroxenites, chromitites, and granites occur in the upper half of the sequence, but are more pronounced and dominant close to the transition zone. Dunite pods and carbonate veins can be found at different stratigraphic levels. Magmatic signatures and monomineralic form of the three ultramafic variety are observed. Where it occurs, chromite-rich variety is always enveloped in olivine- rich pods. Coarse-grained mica-rich granites and pegmatites are well developed below and within the transition zone. Carbonates, and occasionally with serpentine material, impregnate through fractures and structures. The upper mantle peridotite is generally uniform in composition with slight diversity in places. Cr/Al ratio of chromite increases down section, and Mg# of olivine is high reaching 92.5 and low in chromite of chromitite (~ 46). Granitic dikes show higher K relative the crustal sequence dikes. In conclusion, ultramaphic intrusions were formed either by early partial melting of the host peridotite or as invading melt that interacted with host. Granitic dikes may have sedimentary protolith, syn-tectonically intruded the peridotites. Carbonate and serpentine are alteration products of the host minerals most likely obtained during emplacement process.

Dyke swarms of the northeastern Fennoscandian Shield: a key for Paleozoic magma emplacement

Andrei Arzamastsev

Geological Institute of the Kola Science Centre RAS, Laboratory of Magmatism
arzamas@geoksx.apatity.ru

The Kola part of the Fennoscandian Shield is a locus of dyke swarms among which the Proterozoic (PR) and Paleozoic (PZ) dykes are dominant. In order to systematize fragmentary information we collected available data on dyke position, geochronological age, petrography and geochemistry, which are based on our own studies and were taken from reports of geological survey, scientific institutions and publications. The result is organized in a GIS form which contains data on 5740 dykes.

Trend analysis performed for dykes in different basement terrains in the Kola area, give evidence for the two main trends. The NW trending dykes are represented by PR dolerites and PZ alkaline lamprophyres, in which the former are dominant. NE trending dykes are exclusively PZ lamprophyres. These rocks are widespread throughout the whole Kola and northern Karelia and are spatially related to alkaline plutonic massifs. Within the Belomorian mobile belt and Kandalaksha paleorift the Precambrian rocks are overcrowded by alkaline lamprophyres. By contrast, dolerite dykes in the Belomorian are uncommon. They are spread northwest off the Belomorian in the Pechenga - Imandra - Varzuga paleorift, in the Keivy terrane and the Murmansk craton. Geochronological data are sparse and show that dykes correlate the major episodes of igneous activity in the NE Fennoscandia. Almost all PZ dykes show the ages 388 - 362 Ma thus fitting the time span of the PZ alkaline and carbonatite intrusions (Kramm et al., 1993). Our recently obtained age determinations of the Kola (Tersky Coast) kimberlites yield the 40Ar/39Ar age 376.1±2 Ma. Similarly, north-trending dolerite dyke in the Pechenga area give the 40Ar/39Ar age 382±6 Ma. Combined with age determinations of PZ alkaline lamprophyres, which fall within the same time interval (Arzamastsev et al., 2003) these data give evidence for heterogeneous mantle sources for magmatism in the northeastern Fennoscandia which was initiated by the Paleozoic plume activity. (RFBR grant 03-05-64066).

Mafic dyke swarms: The key unlocking Earth's paleogeographic record back to 2.5 Ga

Wouter Bleeker

Geological Survey of Canada, Ottawa, wbleeker@nrcan.gc.ca

Among the geological sciences' most fundamental contributions to the overall body of scientific knowledge are: 1) the concept of deep time; 2) a record of biotic evolution, as preserved in the fossil record; 3) a detailed and mobilistic view of the workings of planet Earth, e.g. plate tectonics; and 4) a record of its evolving paleogeography through time. The latter is very much a work in progress, known only in detail back to ~250 Ma, the time of "maximum packing" of supercontinent Pangaea. Prior to 250 Ma, the paleogeographic record of Earth's continental crust becomes increasingly speculative, although there is growing optimism that this problem may be tractable, in principle, back to ~2.5-2.6 Ga, the age of "cratonization" of a considerable fraction of extant continental crust. Older crustal fragments are either too few in number or too reworked to allow meaningful pre-2.7 Ga global reconstructions, although isolated reconstructions may be constructed for some of the better preserved crustal fragments (e.g., Pilbara and Kaapvaal; or qualitative docking histories within individual Archean cratons).

Of course, going back in time, an increasing number of "pieces of the puzzle" may be missing or their diagnostic information so thoroughly degraded that any reconstruction suffers, inevitably, from increasing degrees of freedom. Continuing attempts to reconstruct ~0.9 Ga supercontinent Rodinia reflect this uncertainty. In addition, in the Precambrian, without a meaningful fossil record and with a paleomagnetic record that is generally more complex, if not overprinted, our toolkit is more limited.

In the last two decades, however, our increasing ability to date many short-lived mafic magmatic events with 1-2 Ma precision has paved the way for perhaps the most robust tool in reconstructing ancient continental paleogeographies. Integrated mapping, high-precision age dating, and paleomagnetism of mafic magmatic events and their dyke swarms allow continental fragments to be placed: 1) at a specific latitude; 2) at a specific time; 3) with known orientation; 4) in a position that optimizes geological continuity prior to break-up and dispersal; and 5) such that the precise piercing points provided by linear dyke swarms are satisfied. In addition, dating all mafic magmatic events provides a "bar code" for each continental fragment. "Best matches" of bar codes can be expected for originally adjacent but now dispersed fragments. Multiple precise ages are also the basis for improved apparent polar wander paths. A concerted international effort (e.g., within the next decade), to date all mafic magmatic events through time and space, would be the most efficient and cost-effective approach to trigger a quantum leap in the understanding of Earth's paleogeographic evolution from 2.5 Ga to the present.

Compilation of diabase dyke swarms and related units for Canada and adjacent regions

Kenneth L. Buchan and Richard E. Ernst

Geological Survey of Canada, Natural Resources Canada, 601 Booth Street, Ottawa, Ontario, Canada K1A 0E8; kbuchan@NRCan.gc.ca

A detailed compilation of diabase dyke swarms and related sills, volcanics and intrusions is now available for Canada, adjacent portions of the United States (including Alaska), and western and southern Greenland (1). More than 450 dyke swarms are displayed on a 1; 5,000,000 scale map, along with several hundred related units. The accompanying catalogue lists details of each (swarm name, location, trend, key references, age, age references, and related units). The swarms range in age from Archean to Present. They vary from giant radiating swarms that cover millions of sq. kms to those that are only of local extent. They may be fresh or metamorphsed, deformed or undeformed. Many swarms represent the plumbing systems for Large Igneous Provinces, the erosional remnants of which are identified as related units in the compilation. A number of the larger swarms are parallel to rift or breakup margins. Work is ongoing to prepare even more comprehensive maps of selected areas. The first of these maps shows dykes and related units of the Slave Province and adjacent Wopmay Orogen of northern Canada. The maps provide a regional framework for correlating undated dykes and related units with known swarms and associated related units. Given the link with rifting and breakup, the distribution and ages of dykes are important for testing paleocontinental reconstructions, both internally within Canada and with formerly adjacent cratons that are now dispersed around the world.

(1) Buchan, K.L., and Ernst, R.E. 2004. Diabase dyke swarms and related units in Canada and adjacent regions. Geological Survey of Canada Map 2022A (scale 1; 5,000,000) with accompanying catalogue (39 pages). [also available in French and on CD-ROM]

Dyke swarms of the Paraná triple junction

Dr. José Moacyr Coutinho

Universidade de Sao Paolo, Departement de Geologia, Mineralogia e Geotectonica, mlcout@osite.com.br

This work, still in progress, intends primarily to survey the field, mineralogical and petrographic characters of the mafic dykes which occur on a stretch of 650 Km along the Southeastern coast of Brazil, between the city of São Sebastião, SP, and the island of Santa Catarina, SC. New chemical and geochronological data are also presented. Most of the accessible dykes outcroping on the rocky sea coast and on the neighboring inland acclivities were visited . The dyke swarms are believed to be components of a plume-generated triple junction related to the initial opening of the South Atlantic. In fact, dilation efforts active along the junction arms allowed the intrusion of mafic magma as dyke swarms along three directions: N-S (Paraná-Santa Catarina coast), NW-SE (Ponta Grossa arch) and NEE-SWW (São Paulo coast). Sixty dykes were mapped on the Paraná-Santa Catarina coast, mostly (85%) composed of tholeiitic and transitional diabases. A few trachites and diorites are also present but only one lamprophyre was detected at the junction zone. The dykes of the Ponta Grossa arch are composed chiefly of tholeitic diabases and lesser andesitic to rhyolitic intrusions. Over two hundred dykes were sampled and identified along the São Paulo arm west of São Sebastião. Lamprophyres are here very abundant (43%) followed by diabases (42%), diorites (10%) and trachite, andesite, carbonatite and Pre-Cambrian dykes (5%). Special attention was given to the study of the São Paulo coast lamprophyres and diabases, their relative abundance, field appearance, mineral and chemical composition, enclaves and age relations.

The form, distribution and anisotropy of magnetic susceptibility of Lower Jurassic dykes in H.U. Sverdrupfjella, Dronning Maud Land, Antarctica. Implications for dyke swarm emplacement

Michael L Curtis[1], William H. Owens[2], Teal R. Riley[1] & Philip T. Leat[1]

[1] British Antarctic Survey, Madingley Road, Cambridge CB3 0ET
[2] School of Geography, Earth & Environmental Sciences, University of Birmingham, Birmingham, B15 2TT

Western Dronning Maud Land, East Antarctica, forms the conjugate margin to south-eastern Africa and contains exposures of Early Jurassic volcanic and intrusive rocks related to the Karoo LIP. Early Jurassic mafic dykes are exposed in nunataks on either side of the Jutulstraumen icestream, which occupies the site of an inferred Jurassic continental rift. In the H.U. Sverdrupfjella region, on the eastern shoulder of the Jutulstraumen rift, approximately 400 dykes were recorded. The majority of the dykes (81%) are doleritic with increased diversity in dyke lithology adjacent to and within the 178Ma nepheline syenite and quartz syenite plutons exposed at Straumsvola and Tvora nunataks, respectively. The dyke swarm has a pronounced NNW-SSE trend with a subcomponent of ENE-WSW trending dykes, although within the Straumsvola nepheline syenite pluton, dykes of almost every orientation are present. Within the swarm, dyke widths display a fractal distribution ranging up to 19.2 m thick, with a mode of 30cm. Dyke spacing follows a log-normal distribution model, with the dykes accounting for 2.06 – 2.63% extension. The swarm shows an increase in dyke spacing and dyke width between Straumsvola and Jutulrøra (15km to the south).

An anisotropy of magnetic susceptibility analysis was conducted on a selection of dykes distributed throughout the study area. 42% of AMS fabrics are normal, 17% inverse and 8% intermediate, while the remainder display no clear fabric relationship to the dyke walls. The majority of the normal fabrics, which are considered to be the product of magma flow, indicate vertical magma flow, particularly adjacent to and within the syenite plutons. Evidence for lateral flow was found in the ENE-WSW trending dykes outside the Straumsvola pluton, with lateral flow indicated for some dykes within Jutulrøra nunataks. The geometric form and distribution of the dyke swarm together with regional variations in dyke lithologies are consistent with the swarm being related to a local magma source centred on the syenite complex. AMS evidence, although not conclusive, is consistent with magma rising beneath Straumsvola and flowing laterally to Jutulrøra, whereas the lateral flow identified in the ENE-WSW trending dykes suggests these dykes may have been be sourced from a separate centre.

Mafic dyke swarms from Southeastern Brazil

Alexandre de Oliveira Chaves[1] & José Marques Correia Neves[1]

[1]*CDTN-CNEN - Belo Horizonte, MG, Brazil. aoc@cdtn.br , nevesj@cdtn.br*

Geological, geochemical, geochronological and magnetometric data concerning mafic dykes from Southeastern Brazil, mainly with tholeiitic affinities, suggest the existence of at least eight swarms[1]. The oldest one (Lavras, 2.65 Ga, Sm-Nd[2]) indicates a late-tectonic Neoarchean extension episode. Dyke emplacement and deformation of the Paraopeba Swarm (2.19 Ga, Rb-Sr[1]) took place inside vertical transcurrent shear zones developed during the Transamazonian Orogeny. During the Late Paleoproterozoic, the area was affected by mantle plume-related rifting, leading to extensive sedimentation (Araí and Espinhaço basins), accompanied by anorogenic felsic plutonism and volcanism, which can be considered, together with the giant Pará de Minas Swarm (1.72 Ga, Rb-Sr[1] and U-Pb[3]), as the bimodal magmatism associated with this rifting[4]. Dykes of the Januária Swarm could be the Brazilian counterpart of the SW Angolan Swarm (ca. 1.25 Ga, K-Ar[5]), which would indicate a Mesoproterozoic extension episode. The Formiga Swarm (1.1-0.9 Ga, Sm-Nd[1],[6] and U-Pb[7]) certainly belongs to the Meso-Neoproterozoic dyke system found in the Congo and São Francisco Cratons[8], recording an important extension event related to a coeval LIP[9]. These five aforementioned Brazilian swarms are found in the São Francisco Craton and they are not intrusive in the cratonic Neoproterozoic cover. The three youngest swarms are mainly found in the Neoproterozoic Araçuaí and Ribeira mobile belts. They are Meso/Cenozoic and show ages of 0.22-0.17 Ga (Transminas, Triassic-Jurassic, K-Ar[6]), 0.13-0.12 Ga (Santos-Rio de Janeiro or Serra do Mar, alkaline, Cretaceous, Ar-Ar[10]) and ca. 0.05 Ga (Arraial do Cabo, Cenozoic, Ar-Ar[11]). These last ones reflect extension events during the Gondwanaland fragmentation. Formiga, Transminas and Santos-Rio de Janeiro (and perhaps Januária) swarms show African counterparts and therefore they are helpful in terms of continental reconstruction.

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Precambrian evolution of the garnet lherzolite mantle beneath southern São Francisco Craton (Brazil) as revealed by Zr/Y ratios of mafic dyke swarms

Alexandre de Oliveira Chaves[1] & José Marques Correia Neves[1]

[1]*CDTN-CNEN, Belo Horizonte, Brazil, aoc@cdtn.br, nevesj@cdtn.br*

Zr and Y contents have been analyzed by XRF for five Precambrian mafic dyke swarms outcropping in the southern Sao Francisco Craton (SF) from southeastern Brazil. These swarms are composed by tholeiitic dykes and intruded SF from Arquean to Neoproterozoic [1]. The oldest ones, named Lavras Swarm (2.65 Ga, [2]) and Paraopeba Swarm (2,19 Ga, [1]), keep the lowest Zr/Y ratios among the swarms, ranging between 2.0 and 5.0. The giant Pará de Minas Swarm (1.72 Ga, [1] and [3]) presents Zr/Y ratios between 5.0 and 7.7. The ratio between these trace elements is from 7.7 to 10.0 for the majority of the dykes from Januária Swarm (1.25 Ga?, [1]) and from 10.0 to 18.2 for Formiga Swarm (1.10-0.90 Ga, [1], [4] and [5]). Therefore the Zr/Y ratio, an useful tool to distinguish dyke generations, is increasing from the oldest swarms to youngest ones.

Garnet lherzolite mantle has been recognized beneath SF by the presence of xenoliths found in Cretaceous kimberlites ([6] and [7]). Xenoliths have very low 188Os/187Os ratios (0.109 to 0.115), similar to those of ancient lithospheric peridotites from Kaapvaal, Wyoming, and Siberian cratons, and yield Re-depletion model ages varying from 1.9 to 2.7 Ga, indicating the presence of Paleoproterozoic/Archean garnet lherzolites beneath SF [7]. Taking into account that dyke tholeiitic magmas should have been extracted from these lherzolites, and the fact that Yttrium is mainly found in garnet, we can propose that the olivine/garnet ratio of the dyke mantle source was decreasing through progressive Precambrian time. Thus, from Arquean to Neoproterozoic the sub-continental mantle beneath SF experienced partial melting processes during dyke generation consistent with progressively higher retention of garnet in the mantle residue. Certainly this sub-continental mantle has become cooler and harder to melt through Precambrian.

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New paleomagnetic, petrophysical and paleointensity results from the Gila County diabases, Central Arizona

Donadini, F.[1], Pesonen, L. J.[1], Korhonen, K.[2], Harlan, S.[3], Deutsch, A.[4]

[1]*University of Helsinki, P.O. Box 64, FI-00014 University of Helsinki, Finland, Fabio.Donadini@helsinki.fi*
[2]*Geological Survey of Finland, P.O. Box 96, FI-02151 Espoo, Finland*
[3]*George Mason University, Fairfax, VA-22030-4444, US*
[4] *Institut für Planetologie, University of Münster, D-48149 Münster, Germany*

Although the paleomagnetically defined positions of most of the continents in the 1.1 Ga old Rodinia supercontinent are reasonably well established, the locations of Kalahari, Grunehogna and Siberia are widely debated. One possible explanation is that the Earth´s magnetic field had a strong non-dipole part at 1.1 Ga ago; this problem is known as the Middle Keweenawan Reversal Asymmetry. In order to tackle this problem we initiated a project, which includes global analysis of 1.1 Ga old paleomagnetic, paleointensity and paleosecular variation, coupled with geomagnetic field modellings. Here we present new paleomagnetic and paleointensity data from the 1.1 Ga old Gila County diabases, Central Arizona, as based on an earlier collection of rocks (Harlan, 1993). The new results show the presence of two polarities in Arizona; a N polarity group with NW declination and moderate downward inclinations, and an R polarity group with variable (mainly SE) declinations and steep negative inclinations. The results thus suggest that there is a strong reversal asymmetry also in Arizona, resembling that in Keweenawan data. The magnetizations of the Arizona diabases are interpreted to be of primary origin. The high temperature susceptibility curves and hysteresis data show generally reversible heating-cooling curves and point to nearly pure pseudo single domain magnetite carriers. The results provide a good basis for paleointensity determinations. The preliminary Thellier determinations show higher intensity values for N polarity rocks (Ba = 13.2 ±4.3 mT) compared to the R polarity rocks (Ba= 9.0 ±5.0 mT). The corresponding equatorial values are BeN = 11.0 mT and BeR= 6.1 mT, respectively. Previous data of the Keweenawan rocks revealed an opposite trend in intensity.

A new survey in Arizona was made by two of us (AD and LJP) in September 2005 extending the sampling from Gila County to the 1.1 Ga old diabases in Sierra Ancha Mountains. Preliminary paleomagnetic results for the new samples will be presented and compared with those from the Lake Superior province of Laurentia, from the Umkondo igneous province in South Africa and from the probably coeval sediments from Siberia (Pavlov). We also analyse the data collectively in terms of the spherical harmonics of the Earth's magnetic field.

The bimodal high-alumina basalt - A-type granite Korsö Dyke, SW Finland

Olav Eklund[1], Sören Fröjdö[2] and Ulf B. Andersson[3]

[1] Dept. of Geology, University of Turku,Turku, Finland
[2] Dept. of geology and mineralogy , Åbo Akademi University, Turku, Finland
[3] Lab. for Isotope Geology, Swedish Museum of Natural History, Box 50007, SE-10405 Stockholm, Sweden

The anorogenic 1.58 Ga Åland-Åboland dyke swarm in SW Finland comprises hundreds of tholeiitic dykes (including some quartz-feldpsar porphyries) of which the Korsö dyke is one of the largest. Trending towards NE, the dyke is exposed over 2500 m along strike and is about 300 m across at its widest point. The dyke is composed of (1) a microgabbroic chilled margin (Mg# ~60, initial $\varepsilon_{Nd\ @1575\ Ma} = -0.3$) containing pl + cpx + opx + pig + ol; (2) coarse-grained ol-bearing gabbronorite, (GabNo; Mg# ~44; $\varepsilon_{Nd} = -0.4$) with a plentitude of elongate pl laths (2-4 cm in length), frequently developing a stellate texture; (3) arfvedsonite-bearing mz-granite A-type affinity (Mg# ~18; $\varepsilon_{Nd} = -1.7$) containing vesicles; and, between the GabNo and mz-granite, (4) a transitional rock (Mg# ~18; ε_{Nd} –1.5) showing affinity with both GabNo and mz-granite. The main rock type is the pl-rich GabNo, locally grading into anorthositic Gab by pl accumulation. The chilled margin outlines the intrusion and in narrower parts appears as a fine-grained dyke, connecting the wider parts.The high amount of pl in the rocks is supported by high contents of Al_2O_3: up to 18 wt.% in the chilled margin and 22 wt.% in the coarse-grained GabNo. Petrologically the GabNo shows similarities to high-Al gab typically associated with Proterozoic massif-type anorthosites. The chilled margin of the Korsö dyke carry euhedral labrador megacrysts, up to 10 cm in size, and large fragments of anorthosite and norite (no) with euhedral pl (An_{55}; ε_{Nd} +1.5) and intercumulus high-Al opx. (Al_2O_3=4-6%, Mg# ~64; ε_{Nd} +0.4). The bulk ε_{Nd} of a no fragment is +0.3. The Korsö dyke is cut by fine-grained dykes (10-50 cm across) enriched in Fe_2O_3 (17.5 wt%), TiO_2 (4 wt%) and P_2O_5 (1. wt%), containing pl + amph + ti + ap and opq. PT-investigations indicate that the no fragments crystallised at approx 6-8 kbar, and that the large euhedral pl formed at approx. 5 kbar. The observed final emplacement level of the dyke is estimated to pressures less than 0.5 kbar and at temperatures of about 1160ºC. The Korsö dyke is an example of polybaric crystallization of Al-rich mafic magmas. The original magma underwent considerable deep level (crust-mantle interface) crystallisation as evidenced by the no fragments, show high Mg#, Al-rich (high *P*) composition of opx, and highest ε_{Nd}. Large euhedral pl crystallised in mid-crustal magma chambers and anorthositic rocks formed. Samples of these rock types from different crustal levels were brought up by a hot, Al-saturated GabNo that was emplaced at sub-volcanic levels. The rapid rise of the high-Al magma that upon decompression became significantly oversaturated in pl is indicated by the presence of stellate pl. Late stage magmas (Fe-Ti enriched) appear as dykes cutting the complex. As evidenced by varying ε_{Nd}, the magmatic differentiation worked by open system processes in which crustal material was succesively incorporated during the magmatic evolution.

Basic dykes and dyke swarms in central and northern Sweden and the plate tectonic evolution of Fennoscandia: palaeomagnetic and Ar^{39}/Ar^{40} studies

Sten-Åke Elming

Division of Ore Geology and Applied Geophysics, Luleå University of Technology, 97187 Luleå, Sweden, sten-ake.elming@ltu.se

Palaeomagnetic and Ar^{39}/Ar^{40} studies have been performed on basic dykes and dyke swarms in central and northern Sweden. At least five different generations of dykes have been defined and will be discussed in a plate tectonic context. Reliable palaeomagnetic data have been obtained from a big gabbro diabase and a geographically related dyke swarm in the northern part of Sweden from which poles similar to those calculated from Svecofennian gabbros (ca 1.86 Ga) are defined. In another swarm of palaeomagnetically similar age, just north of the Skellefte district, partially remagnetized dykes indicate a possible Subjotnian or Caledonian regional remagnetization. The dykes are younger when moving towards the south and in the central part there is a significant dyke swarm with at least two generations of dykes (ca. 1.7 and 1.6 Ga, respectively), one of which is related with rapakivi magmatism. Palaeomagnetic and anisotropy of magnetic susceptibility (AMS) data from the huge ca 1.25 Ga sill complexes in central Sweden and western Finland and from basic intrusions in Greenland suggest that Baltica and Laurentia were joined at that time. The similar stress field as indicated by the AMS data and the tensional regime reflected by the sill complexes is interpreted related to the break up of Baltica from Laurentia. New data from ca 1.1 Ga dykes in central Sweden confirms a clockwise rotation of Fennoscandia between 1.25 and 1.1 Ga, a rotation that is not seen for Laurentia.

A palaeomagnetic study of Mesoproterozoic basic dykes from the Ukrainian Shield and the amalgamation of the shield with Fennoscandia

Sten-Åke Elming[1] and Svetlana Kravchenko[2]

[1] *Division of Ore Geology and Applied Geophysics, Luleå University of Technology, 97187 Luleå, Sweden, sten-ake.elming@ltu.se*
[2] *Geophysical Institute, Academy of Sciences of Ukraine, Kiev, Ukraine.*

A palaeomagnetic study has been performed on Palaeo-Mesoproterozoic basic intrusions from three crustal blocks of the Ukrainian Shield. At least three different generations of dykes has been identified and positive field tests can be demonstrated for some of them. A sequence of 2.1 to 1.72 Ga apparent polar wander has been defined on basis of the new palaeomagnetic and Ar/Ar data presented here and on basis of old data from anorthosites. The calculated poles are significantly different from poles of similar age from the Fennoscandian Shield. Although the poles are not perfectly coeval the tectonic reconstructions demonstrate that the Ukrainian Shield collided with Fennoscandia at 1.80-1.85 Ga and then rotated some 45° into its present relative position.

Dyke swarms and the Global Large Igneous Province (LIP) Atlas Project

Richard E. Ernst and Kenneth L. Buchan

Geological Survey of Canada, Natural Resources Canada, 601 Booth St., Ottawa, ON K1A 0E8, rernst@NRCan.gc.ca;

Large Igneous Provinces (LIPs) are high volume, generally short duration pulses of magmatism that punctuate Earth's history, perhaps as often as every 10 to 20 million years. Many LIPs are larger than one million cu. km. The largest is 'greater' Ontong Java with a volume of 58 million cu. km. Most are dominated by mafic magmatism. Many have been linked with mantle plumes and related regional domal uplift. In addition, they are commonly associated with rifting and continental breakup, may have a significant effect on global climate, and are highly prospective for Ni-Cu-PGE mineral deposits.

LIPs of Mesozoic and Cenozoic age are dominated by flood basalts. In the Archean, the most promising LIP candidates are tholeiitic greenstone belts containing komatiites. In the broad intervening time interval (Paleozoic and Proterozoic) the flood basalt component is typically deeply eroded exposing the LIP plumbing system. This plumbing system consists of sill provinces, layered intrusions and, most prominently, giant dyke swarms. Those giant dyke swarms that radiate can be used to locate the centres of mantle plumes. Some sill and volcanic packages are thought to be fed laterally via giant dyke swarms from mantle source areas up to >1000 km away.

A three year project has begun on a comprehensive global digital atlas of LIPs. The Atlas will contain the digitized distributions of all LIP-related volcanic packages, layered intrusions, dyke swarms and sill provinces. The focus will be on mafic-ultramafic magmatism, but related silicic magmatism will also be included. The Atlas will incorporate both the mapped surface expression of units and their inferred subsurface extents based on drill core information and geophysics. Sources of information will be fully referenced. The Atlas is being prepared under the auspices of the Large Igneous Provinces (LIPs) Commission (www.largeigneousprovinces.org). The preliminary strategy is to focus on North America and Europe/Asia in the first year, Australia and Africa in the second, and South America and Antarctica in the third. Information on oceanic LIPs will be integrated in years 1 and 2.

Origin of mafic and ultramafic rocks at Munali nickel deposit, Zambia: Implications for Neoproterozoic mantle evolution in Eastern Africa

David Evans[1], Donal Windrim[1], Simon Johnson[2] & J Andrew Milton[3]

[1]*Albidon Ltd., 141 Broadway, Nedlands 6009, Western Australia*
[2]*JAMSTEC, 2-15 Natsushima-Cho Yokosuka 237-0061, Japan*
[3]*School of Oceanography and Earth Science, Southampton University, U. K.*

Nickel occurs within a series of subparallel massive sulphide veins and breccia/stockwork zones associated with a variety of Mg-rich rocks at the margins of a 2.6 km long gabbro body at Munali, southern Zambia. The gabbro body is Fe-rich and compositionally homogeneous, with fine and coarse-grained phases. It intrudes metamorphosed Neoproterozoic marbles and calc-silicates, near the boundary with a Mesoproterozoic granitic gneiss inlier within the Pan-African Zambezi Belt. Field evidence suggests that the mafic igneous rocks are pre- to synorogenic, having undergone brittle-ductile deformation and lower greenschist metamorphism. Textural evidence suggests that the Mg-rich rocks are a late phase intrusion. Carbonate veining and alteration affects all of the above rock types to varying extents. The sulphides are spatially and texturally associated with Mg-rich rocks at the margin of the main gabbro body. These rocks vary from altered tremolite-talc-carbonate rocks to texturally well-preserved serpentinites and dunites. Where well preserved, the dunites are coarse-grained (>5cm olivines) and contain interstitial to net-textured magmatic sulphides, magnetite and apatite, but no chromite, and very little pyroxene or feldspar. The olivine has a composition of Fo77. The dunites are intimately mixed with very fine-grained olivine dolerite, which appears to be a late intrusive phase, but more or less coeval with the emplacement of the dunites and molten sulphides. Completely altered, small olivine phenocrysts in the dolerite can be recognized by their hopper morphology. The mineralogy of specimens suggest that the Fe-rich gabbros and the Mg-rich ultramafic rocks might be comagmatic, if so they must be products of differentiation of an olivine-tholeiitic melt at a greater depth than the current level of emplacement. Whole rock analyses of the mafic and ultramafic rocks are currently being undertaken and zircon extracted from coarse pegmatitic phases of the gabbro will be dated by LA-ICPMS.

The presence of ultramafic rocks associated with Pan-African gabbros is unusual in Zambia. The Fe-rich nature of both the gabbros and ultramafic rocks suggests they may be the products of differentiation of a tholeiitic parent. Their proximity to a major structural break between Mesoproterozoic basement and Neoproterozoic continental cover sequences could imply an extensive vertical series of magmatic staging chambers, ultimately derived from a more primitive mantle melt resulting from a mantle thermal anomaly. Comparisons with other Neoproterozoic mafic suites will be made.

Development of parallel dike swarms and cone sheets controlled by the change of magma supply rate: dike swarms of the Miocene Otoge igneous complex, central Japan

Nubuo Geshi

Geological Survey of Japan, geshi-nob@aist.go.jp

Basaltic - andesitic dike and sheet swarms of the post-cauldron activity of the Miocene Otoge igneous complex, central Japan show systematic structural and petrological evolution. A concentric cone sheet swarm (Otoge cone sheets) measuring 10 to 15 km^3 was formed at the beginning of the post-cauldron stage and was later succeeded by the formation of a parallel dike swarm (Shitara central dike swarm) measuring 3 to 5 km3 within half million years. The Otoge cone sheets have a less-fractionated character with little compositional variations, whereas the Shitara central dike swarm has a fractionated character with wide compositional variations; this despite that both swarms reflect a single fractionation trend. The compositional change from the Otoge cone sheets to the Shitara central dike swarm can be explained by fractional crystallization due to the decline in the supply of less-fractionated hot magma into the reservoir.

The stress field controlling the orientation of dikes is generally a combination of a local stress field formed by the magma reservoir and a regional stress field. The excess pressure of the reservoir creates a local compressive stress field around the reservoir, which is suitable for intrusion of concentric cone sheets. When the compressive stress field around the reservoir is weak, the effect of the regional stress field becomes notable on the development of dikes and a parallel dike swarm will be formed. Structural difference between the Otoge cone sheets and Shitara central dike swarm will reflects the change of the stress stage around the magma reservoir by the change of internal excess pressure of the reservoir. The structural change from the Otoge cone sheets to the Shitara central dike swarm reflects the change in the stress field from a local compressive field to a regional extensive one, with the decline of magma replenishment into the reservoir during the final stage of volcanic activity.

A possible cause of the excess pressure in the magma reservoir is magmatic injection, because injection of magma into a reservoir causes rapid increase in excess pressure in a magma reservoir. Compositional difference between these two intrusive swarms shows the decrease of the magmatic input to the reservoir during the formation of these intrusive swarms. Relatively less-fractionated character of the Otoge cone sheets indicates the high input rate of mafic magma into the reservoir. The evolved composition of the Shitara central dike swarm, by contrast, suggests the progress of fractional crystallization within the reservoir under low magmatic supply rate. The Otoge cone sheet is more than 10 km^3 in total volume and is the largest intrusive unit during post-cauldron activity and this suggests the high-magma supply rate at the formation of the Otoge cone sheets. The volume of the Shitara central dike swarm is much smaller than that of the Otoge cone sheets, and this also suggests a decrease in the magmatic supply during the formation of the Shitara central dike swarm. These observations suggest that the high injection rate of the mafic magma into the reservoir during the formation of the Otoge cone sheets caused the high excess pressure in the reservoir, which formed a compressive local stress field in the vicinity of the reservoir. Decrease of the magma input to

the reservoir during the formation of the Shitara central dike swarm caused the decreasing of the excess magmatic pressure of the reservoir and the local compressive stress field disappeared.

Lu-Hf and U-Pb of zircon from the Jomasknutene Gabbro, Bamble Area, southern Norway

Stuart Graham[1], Tom Andersen[1], Geert-Jan de Haas[2]

[1]*Institutt for geofag, Oslo University, Norway stuart.graham@geo.uio.no, tom.andersen@geo.uio.no*
[2] *Nuclear Research and Consultancy Group, Petten, The Netherlands*

The use of laser ablation multiple collector (MC)-ICPMS to determine U-Pb and Lu-Hf isotope ratios in individual zircons is a technique that allows rapid data accumulation from a large number of individual zircons. The laser ablation method yields similar data, i.e., petrogenetic and age, to wet chemical methods U-Pb (zircon) and Sm-Nd (whole rock), although in a fraction of the time, and is proving incredibly valuable in provenance and igneous petrogenesis investigations. Furthermore, as both isotope ratios are obtained from the same zircon the interpretations have far more genetic significance than U-Pb and Sm-Nd TIMS (SHRIMP) data.

As an example of the utility of this technique we have used the newly installed Oslo University Nu-Plasma MC-ICPMS connected to a Nu-Wave Nd:YAG 213 nm laser to determine the U-Pb and Lu-Hf isotope ratios in zircons from the Jomåsknutene gabbro in southern Norway. This rock is somewhat controversial, as previous attempts to determine its emplacement age – Sm-Nd (whole rock), U-Pb (zircon – TIMS & SIMS) and LA-ICPMS (single collector) have produced circumspect results. No useable data were obtained by the TIMS or SIMS methods. The whole rock Sm-Nd age of 1770 ± 190 Ma, and depleted mantle initial 143Nd/144Nd, is circumspect because they imply that the gabbro is one of the oldest crustal elements in an area of the Bamble Terrane where other gabbroic and granitic rocks were emplaced at 1250 Ma.

Using LA-MC-ICPMS, we find two groups of zircons in the Jomåsknutene gabbro – both of which lie very close to concordia on a 207Pb/235U vs 206Pb/238U isotope diagram. The data display a precision equal to that of SHRIMP, attesting the usefulness of the technique. We interpret the ages as representing, 1) emplacement 1235 ± 13 Ma (MSWD = 0.6), and 2) subsequent metamorphism at 1097 ± 13 Ma (MSWD = 1.2). Results consistent with previous U-Pb and Sm-Nd studies from other Bamble Terrane rocks.

Mesoproterozoic dyke swarms in central Scandinavia, their distribution, Caledonian overprint and geochemistry

R. O. Greiling[1], J. C. Grimmer[1], H. de Wall[2], L. Björk[3]

[1] Geologisch-Paläontologisches Institut, Universität Heidelberg
[2] Geologisches Institut, Universität Würzburg
[3] Sveriges Geologiska Undersökning, Uppsala

The Central Scandinavian Dolerite Group (CSDG) comprises dyke swarms and sills, intruded into the Fennoscandian Shield at c. 1.265 Ga ago. Towards west, the Shield is overlain by a thin, discontinuous sedimentary cover of late Neoproterozoic to Ordovician age and the fold-and-thrust belt of the Caledonian orogen. The large-scale geometry of the CSDG can be well determined from magnetic anomaly maps, which show at least two different sets of straight, ENE-WSW and NW-SE trending dykes, respectively. Thin dykes (c. 1m) show a well-developed chilled margin, locally with a sub-microscopic grain size. The interior parts show coarse-grained ophitic intergrowths of pyroxene and plagioclase, with subordinate opaque minerals and olivine. Towards west, the CSDG dykes are distributed exclusively within the crystalline parts of the Caledonian Lower and Middle Allochthon thrust units, and have nowhere been observed to cut the (late) Neoproterozoic cover sequences. In the Lower Allochthon dykes retain sharp contacts against the country rocks. In low strain domains, dykes with their primary contact relationships and primary, ophitic texture are well preserved. In high strain domains, dykes appear as sheared zones in the field and show a completely transposed planar fabric with a secondary, lower greenschist mineral assemblage. In the Middle Allochthon, dykes are generally sheared. Whilst at low strains, m-scale dykes with patches of altered plagioclase phenocrysts can still be discerned, highly sheared dykes are drawn out to thin layers of cm thickness.

88 samples from 39 locations were analyzed for major elements and 71 also for trace elements. Major elements indicate alkaline basalts. Trace elements Zr, Y, and Nb reveal within-plate alkali basalt, within-plate tholeiite, and N-MORB signatures and thus increasing degrees of partial melting. In some dikes high Na, K, and Rb contents may indicate crustal contamination. In the Lower Allochthon dykes, K-contents are very high in some samples (up to 5.66%). The strong K-Rb correlation suggests homogeneous, high temperature contamination. In the dikes of the Middle Allochthon K and Rb correlate very well, indicating no major inhomogeneous contamination. The CSDG is contemporaneous with intra-continental basin (aulacogen) formation, and precedes continental break-up prior to Grenville orogeny. CSDG dykes in the Caledonian nappes indicate a much wider westward extension than was known earlier, until at least the present Atlantic margin. This geometry may be important for pre-Grenville plate reconstructions, e. g. links with the Mackenzie dyke swarm.

Dyke swarms and continental deformation

Henry C. Halls

University of Toronto, Department of Geology, Erindale College, 3359 Mississauga Road, Mississauga, Ontario, L5L 1C6, Canada, hhalls@utm.utoronto.ca

Proterozoic dyke swarms cutting Archean shield areas of the world are well known as structural markers that can be used to highlight deformation of a shield in the vicinity of major fault zones. Excellent examples occur in Greenland, Canada and Uruguay. Where dykes are fresh, and undeformed on a local scale, paleomagnetic measurements across a large swarm can detect broad scale crustal rotations. Often this deformation is accompanied by uplift, expressed in dykes by a remagnetization attendant upon the growth of magnetite and other minerals in feldspar. This secondary growth leads to clouding of the feldspar which increases with dyke emplacement depth. An example of the use of feldspar clouding, paleomagnetism and U-Pb dating to define Proterozoic deformation of the Archean Superior Province of Canada will include a demonstration that the two halves of the Canadian Shield on either side of Hudson Bay have experienced vertical-axis rotation with respect to one another of about 20°. The correlation of dyke swarms on a more global scale is a potentially powerful tool to reconstruct past configurations of continents. Successful attempts have been made to link swarms between Africa and South America and between Canada and Greenland, but as yet no swarms have been convincingly matched that lead to more exotic configurations often seen in supercontinent configurations.

One example, from the Canadian Arctic and northern Greenland, will be shown that attempts, using paleomagnetism and U-Pb age data, to match two E-W trending swarms, the Thule dykes of Greenland and dykes on Devon Island in Canada. If these swarms, which are approximately 700 Ma old, were once joined, they have since been offset sinistrally about 200 km along a fault lying beneath Davis Strait that separates the two land masses. This fault was originally proposed by Alfred Wegener in order to restore Greenland to Canada by closing the Labrador Sea, but it is controversial because it is not supported by geological evidence.

Sims zircons ages and Nd isotope systematics of the 2.22 Ga mafic intrusions in Northern and Eastern Finland

Eero J. Hanski[1], Hannu Huhma[2] and Jouni I. Vuollo[3]

[1]*Department of Geosciences, P.O. Box 3000, FIN-90014 University of Oulu, Finland*
[2]*Geological Survey of Finland, P.O. Box 96, FIN-02151 Espoo, Finland*
[3]*Geological Survey of Finland, P.O. Box 77, FIN-96101 Rovaniemi, Finland*

One distinct phase of the Paleoproterozoic mafic magmatism in Finland is represented by the ca. 2.2 Ga layered sills assigned to the gabbro-wehrlite association (GWA). These gravity-differentiated mafic-ultramafic bodies are widely spread in eastern and northern Finland and reach more than 100 km in length and several hundred meters in thickness. Most often they occur close to the base of the Karelian supracrustal belts, intruded into Jatulian quartzitic metasediments, but similar intrusions have also been found within the Archean Kuhmo Greenstone Belt.

Using the SIMS, ID-TIMS and Sm-Nd isotopic methods and the electron microprobe, we have studied differentiated mafic intrusions of the GWA from several Proterozoic schist belts and the Archean Kuhmo Greenstone Belt. Back-scattered electron images and electron microprobe analyses revealed that zircon crystals vary from well-crystallized to highly metamict and altered with individual grains often displaying irregular, hydrated, CaO-bearing domains In the most pristine domains, suitable for establishing the crystallization ages, SIMS $^{207}Pb/^{206}Pb$ ages fall in the range of 2210–2220 Ma, which are consistent with the most concordant ID-TIMS U-Pb ages. One of the studied intrusions that had previously yielded a conventional U-Pb date of less than 2.0 Ga, could be shown by spot analysis to belong to the 2.2 Ga family. In contrast the pristine domains, the altered domains exhibit a variable and often strong U-Pb discordance up to 70% and have distinctly lower $^{207}Pb/^{206}Pb$ ages. Some zircon grains record isotopic resetting at the time of the Svecofennian orogeny (ca. 1.8 – 1.9 Ga) while the most discordant ones project in the concordia diagram to late Paleozoic lower intercept ages indicating a relative recent Pb loss. The mineral chemistry of zircon suggests that the loss of radiogenic Pb can be ascribed to an open-system behaviour related to hydrothermal alteration via action of $CaCl_2$-bearing fluids.

Common albitization of plagioclase in the GWA intrusions has caused this mineral to behave as an open system with regard to the Sm-Nd isotopic systematics. Despite this uncertainty, our Nd isotopic data indicate that the magma that produced the GWA intrusions in various parts of Finland was isotopically homogeneous and had an initial ε_{Nd}(2220 Ma) value of ca. +0.6 precluding significant crustal contamination upon emplacement and subsequent fractional crystallization.

Earth and Planetary Dike Emplacement: Insights into Geological Processes and Planetary History

James W. Head[1] and Lionel Wilson[2]

[1]*Dept. of Geological Sciences, Brown University, Providence, RI, USA, james_head@brown.edu*
[2]*Environmental Science Dept., Lancaster University, Lancaster, UK, L.Wilson@Lancaster.ac.uk*

The processes of magmatic intrusion, dike emplacement and surface volcanic eruption provide important information about the nature of planetary heat sources, mantle heterogeneity, planetary heat transfer processes, the state of stress in planetary lithospheres, planetary thermal evolution, planetary surface conditions, and compositional and thermal layering in planetary interiors. We review the importance of dike emplacement in the evolution of the terrestrial planetary bodies besides Earth, and emphasize outstanding problems and how new data can help advance knowledge in these areas.

The Earth's Moon: Linear graben with associated pyroclastic cones and other eruptive products [1] provide evidence for the presence of dike-intrusion to shallow depths. Gas release at great depths due to low-pressure zones in dike tips is an important process in forming dike-related pyroclastic eruptions [2]. The array of dike-related features (graben, pit chains, and small edifices) provides information on the nature of shallow crustal processes. Eruptions through dikes on the Moon are characterized by infrequent emplacement and typically very high-volume eruptions [3]. New altimetry and gravity data are needed to further test paradigms about the role of crustal and thermal structure in creating buoyancy barriers to magma rise, dike emplacement and surface volcanism.

Mars: Ample evidence exists for the formation of extensive dike swarms around major volcanic edifices and provinces [4]. Dikes can extend for thousands of kilometers and many swarms resemble mafic dike swarms on Earth [5]. Furthermore, dike emplacement has been identified as one of the major processes linked to the cracking of the global cryosphere, permitting the catastrophic release of subsurface groundwater under hydrostatic pressure, and the extensive regional water flooding of the surface [6]. Recently, huge phreatomagmatic eruptions have been recognized around such dike-emplacement events [7]. Dike outcrops have been identified in the walls of Valles Marineris; and in the Tharsis region, huge tropical mountain glacier deposits [8] show evidence of the original glaciers having been intruded [9] by dikes and sills (subglacial lava flows) [10, 11]. Magnetic anomalies in the southern hemisphere of Mars have been interpreted by some to be remnants of huge mafic dikes. New higher-resolution magnetometer, imaging and spectrometer data will enhance our understanding of these processes.

Venus: Formation of neutral buoyancy zones and lateral propagation of dikes to produce mafic-dike-swarm-like features was a common occurrence across the surface of Venus [12]. These features provide a laboratory for the documentation and analysis of the possible surface manifestations of Archean mafic dike swarms on Earth now only exposed at depth [13, 14]. Furthermore, graben associate with dike emplacement on Venus can be used to map patterns of lithospheric strain [15]. Crosscutting graben relationships can be used to establish regional geological histories and temporal relationships among regional geologic units [16], and

graben geometries can provide information on the characteristics and duration of magma rise [17] and comparisons to similar pressure environments (submarine) on Earth [18, 19].

Mercury: Little evidence is observed for features that might represent the surface manifestation of dikes, due primarily to incomplete imaging coverage and low resolution. Indeed, there is uncertainty as to whether effusive volcanic deposits even occur on Mercury [20]. The MESSENGER spacecraft en route to Mercury and BepiColombo, in the planning stage, will provide the surface resolution to address these issues globally.

Summary: Significant progress has been made during the first part of the Space Age in the understanding of the importance of dike-emplacement processes on the planets and how this knowledge can be used to understand planetary evolution.

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Sm-Nd isotopes in Paleoproterozoic mafic rocks in Finland – rifting of Archean lithosphere and mantle sources

Hannu Huhma[1], Eero Hanski[2] and Jouni Vuollo[3]

[1]Geological Survey of Finland, P.O. Box 96, FIN-02151 Espoo, Finland
[2]Department of Geosciences, P.O. Box 3000, FIN-90014 University of Oulu, Finland
[3]Geological Survey of Finland, P.O. Box 77, FIN-96101 Rovaniemi, Finland

Isotopic studies on mafic dikes, intrusions and volcanic rocks in Finland have revealed that rifting of the Archean lithosphere took place at several stages, e.g., 2.44 Ga, 2.3 Ga, 2.22 Ga, 2.15 Ga, 2.1 Ga, 2.05 Ga, 2.0 Ga, 1.8 Ga. These are well exemplified in the special volume containing U-Pb data on more than 180 samples from Finnish Lapland (Vaasjoki, 2001, editor, Geological Survey of Finland, Special Paper 33, 279 p). Many of these results date gabbroic rocks from intrusions and dikes, and can also be used to constrain the age of mafic volcanism, which has produced major formations especially in Central Lapland. Mafic rock associations in the Karelian domain provide samples from the mantle below the Archean craton, and may be considered as Large Igneous Provinces.

Since early 80's Sm-Nd mineral and whole-rock analyses have been made at GTK. The database includes more than 400 analyses on ca. 60 Paleoproterozoic mafic rock units in the Karelian domain. The emphasis has been on most pristine mafic rocks available, and generally Sm-Nd mineral ages on 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 geochemical and other geological information provide tools for constraining the age and origin of mafic magma and the evolution of the lithosphere.

The initial ε_{Nd} values range from very positive to strongly negative and suggest that some rocks were derived from a depleted mantle source whereas others have a large contribution from old enriched lithosphere. Deep-crustal contamination of ultramafic magma may explain many features observed in mafic-ultramafic rocks (e.g. 2.44 Ga mafic intrusions with ε_{Nd} of –2), but the isotopic results also show that various mantle sources with distinct isotopic compositions have existed during the Paleoproterozoic. Examples are provided by high-REE mantle-derived rocks, which show a range of initial ε_{Nd} values from nearly chondritic (e.g. 2.6 Ga Siilinjärvi carbonatite, 2 Ga Jormua OIB, 1.8 Ga lamprophyres) to highly positive (e.g., the ca. 2 Ga Laivajoki and Kortejärvi carbonatites).

Correlating dyke generations to associated lava formations in the northern Lebombo monocline, Karoo large igneous province, South Africa

M.B. Klausen[1], J.S. Marsh[2] and Watkeys, M.K.[3]

[1]EGRI, School of Geosciences, University of the Witwatersrand, Wits 2050, South Africa (SA), klausenm@geosciences.wits.ac.za
[2]Department of Geology, Rhodes University, Grahamstown 6140, SA, goonie.marsh@ru.ac.za
[3]School of Geological Sciences, Univ. of KwaZulu-Natal, Durban 4041, SA, watkeys@ukzn.ac.za

A magnificent transect across a combined lava section and associated feeder dike swarm has been mapped and sampled, ~240 km from a triple junction between the Okawango dike swarm and the Mwenezi- and Lebombo monoclines; i.e., the presumed centre of the Karoo large igneous province. The 32 km-long transect across the eastward-verging northern Lebombo monocline and associated 'Balule' dyke swarm follows the Olifants River, exposing (1) tephritic base flow(s), (2) a lower basaltic sequence, (3) a overlying basaltic sequence with inter-bedded rhyolitic and plagioclase-porphyritic flows, (4) a rhyolitic sequence with inter-bedded basaltic flows, and (5) an uppermost rhyolitic sequence mapped to the Mozambique border. Eastward of a conspicuous western (inland) dyke swarm margin, the entire sequence of lavas is cut by a dense swarm of roughly N-S trending dykes and several clusters of more westerly striking, oblique dykes. A field correlation of at least five generations of conspicuous dyke types to overlying characteristic lava formations is supported by an eastward decline in dyke densities, along the transect and up through the tilted lava pile.

Field evidence will on this poster be evaluated by ongoing geochemical correlations (for example, by applying a correspondence analysis) between ~200 dyke samples and ~200 lava samples. Just from looking at geochemical variations up through the basaltic part of the lava sequence, it seems that even a correlation between mafic dykes and lavas will be feasible. Major element variations show a temporal decrease in SiO_2, with a concomitant increase in FeO_{Tot}, TiO_2 and MnO, which is attributed to extreme degrees of Fe-Ti oxide undersaturation during silicate fractionation (i.e., an extremely Fe-enriched AFM-trend). Increasing total alkalies (mainly Na_2O) with decreasing SiO_2 also reflect a change towards more trachy-basaltic compositions, which is progressively overtaken by rhyolitic volcanism. Incompatible trace elements do not exhibit much systematic variation up through the basaltic pile, where only a slight decrease in Zr follows SiO_2 and Nb shifts towards higher concentrations at the onset of rhyolitic volcanism. At this marked stratigraphical Nb shift, the basaltic pile also separates into a (Cr,Ni)-rich lower and (Cu,V)-rich upper half that possibly reflects incomplete olivine fractionation and increased sulfur solubility, respectively.

Dyke swarms in the eastern Tibetan Plateau (Sichuan Province, China)

M.B. Klausen[1], Y. Yao [1], J. Kramer [1], A.H. Wilson[2] and G. Chunnett[3]

[1]EGRI, School of Geosciences, University of the Witwatersrand, Wits 2050, South Africa (SA), klausenm@geosciences.wits.ac.za, kramerj@geosciences.wits.ac.za, yaoy@geosciences.wits.ac.za
[2]School of Geosciences, University of KwaZulu-Natal, Durban 4041, SA, wilsona@ukzn.ac.za
[3]Anglo Platinum, 55 Marshall Street, Johannesburg 2001, SA, gchunnett@angloplat.com

At the eastern margin of the Tibetan Plateau (Sichuan Province, China), close to the village of Danba, a mafic dyke- and sill complex, tentatively related to the Late Permian Emeishan Large Igneous Province (LIP) on the south-western margin of the Yangtse (North China) Craton, intrudes meta-sedimentary sequences of predominantly Paleozoic shales and limestones, as well as a coarse grained, supposedly Permian, granite intrusion. This composite crustal sequence has been subjected to up to amphibolite facies conditions (possibly during the Late Triassic Indosinian orogeny) and has been brittely deformed during the Cenozoic Himalayan orogeny. While most igneous intrusions are strongly foliated and boudinaged, dyke geometries are better preserved within the granite. A magnificent 9 km wide section through the dyke swarm is exposed along the Dadu River (SSE of Danba), along which ~500 dykes and ~250 fractures and faults have been mapped and 18 dykes were sampled for petrological studies. At least three different types of ~N-S trending dyke swarms were injected into the granite. An early generation of felsic dykes, which in turns are cut by pale grey, intermediate dykes, followed by dark grey, mafic dykes. Some felsic dykes have cuspate contacts with the granite host and mafic dykes often cluster in a 'braided' fashion, both possibly reflecting injections into locally softened granite. Compared to the pervasively deformed meta-sediments, the more competent granite accommodated localized post-Permian deformation along shear zones. Especially thinner, less competent mafic dykes accommodated straining, as evidenced by foliation at low angles to dyke margins and supported by bimodal (concave-upward negative exponential) frequency-thickness distributions. Ongoing rigorous reconstructions will serve to elucidate the original dyke swarm geometry, which, in conjunction with geochemical characterization and comparison with both personal unpublished and published data sets, will examine its proposed relationship to the Emeishan LIP. A correlation will have implications for further reconstructions of this LIP, e.g., whether it developed a volcanic rifted margin, as well as the area's ore mineralization potential.

Pudasjärvi mafic dyke; geophysical and petrophysical interpretation

Juha Ville Korhonen

Geological Survey of Finland, Espoo Unit, PO Box 96, 02151 Espoo, Finland
juha.korhonen@gtk.fi

Pudasjärvi dyke crosses Archaean Pudajärvi block in N-S direction for a length of 180 km. It consist of 30 parts, right handed en echelon. The eldest rocks of the host block are dated back to Mesoarchaean and younger part to Neoarhaean. The dyke don't cross the neighboring Palaeoproterozoic schist basins. The dyke is not exposesd anywhere to the Earths surface. Hence it is indicated by magnetic and gravity anomalies only. Two drillings have been made. To the north (Ranua) the core intersects a metadiabase and an albite diabase, to the south (Vaala) the core represents a differentiated, coarse grained metadiabase of width 40 m, dipping deeply to the east. In the latter core the hanging wall contact is tectonic. At the foot wall the dyke mixes with host rock melt. The dyke consists of several phases with different petrophysical characteristics, indicating several intrusion phases, differentiation and – probably – different magma sources. The dyke is strongly magnetic; susceptibility corresponds to 3.2 per cent of coarse grained magnetite on average. Mean total magnetization is 6.1 A/m and bulk density 3000 kg/m^3. Paramagnetic population has been detected at the hanging wall, representing ca. 2 per cent of the dyke width. No comparabel highly magnetic dyke is known in the Finnish Archaean. The magnetic properties correspond closely to 2200 Ma old Gabbro-Wehrlite association, represented by dykes and sills close to Finnish Archaean-Proterozoic boundary. Hence it may be interpreted to belong to this dyke forming event. Its length and setting reveal that it may be connected with a major tectonic event in the beginning of accumulation of Palaeoproterozoic Jatulian sequence of supracrustals, which ultimately lead to rifting and opening of sea between two parts of the Jatulian continent of Archaean origin. The dyke may represent a deep section of a feeding channel of Jatulian gabbro-wehrlite dyke system.

Mafic dykes as tracers of lithospheric mantle domains beneath Antarctica

Philip T. Leat

British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, U.K.
p.leat@bas.ac.uk

We have collated new and published data for mafic dykes and volcanic rocks from Antarctica in order to identify mantle domains beneath the continent. We have identified a set of mafic magmas as being derived from lithospheric mantle. These include lamproitic, some lamprophyric, and basaltic rocks. Most were very resistant to contamination of their Nd and Sr isotope values by continental crust because the very low degrees of mantle partial melting that produced the melts gives them high abundances of Sr and Nd relative to the crust. Those from Archaean (>2.5 Ga) to Middle Proterozoic (>1.0 Ga) cratonic and circumcratonic areas of East Antarctica have time-corrected ε_{Nd} values of -20 to -3. This demands isolation of the LREE-enriched sources within pockets of stable sub-cratonic lithosphere for more than 1 Ga, consistent with the current lithosphere thickness up to 250 km imaged by seismic tomography. In contrast, lithosphere-derived mafic rocks from Middle Proterozoic to Early Palaeozoic areas of West Antarctica, Victoria Land and the Falkland Islands (adjacent in Gondwana) that formed the Gondwana continental margin, have time-corrected ε_{Nd} values of -3.6 to +3.5, implying more recent isolation from asthenosphere. This also supports geophysical evidence for thin lithosphere, and hence high heat flow, in West Antarctica. It is also consistent with the Phanerozoic accretion history of West Antarctica seen, for example in the amalgamation of arc terranes in the Antarctic Peninsula. In terms of mantle reservoirs, cratonic and circumcratonic areas trend toward EMI, with EMII possibly being a minor component. Gondwana margin areas trend toward EMII, with EMI being at most a very minor component.

New criteria to recognize the azimuth and the dip of a subduction just looking at the AMS data across its associated mafic dyke swarm. A 3 D geophysical and structural approach.

Jean-Pierre Lefort[1], Tahar Aïfa [2] and Francisco Hervé [3]

[1] *Institute of Tectonophysics, Allée des Lucanes, Chemin des Cavaliers, Le District, 35250, Saint-Sulpice-la-Forêt, France, jean-pierre.lefort5@ wanadoo.fr*
[2] *Geophysics, Géosciences-Rennes. Campus de Beaulieu, 35042 Rennes cédex, France tahar.aifa@univ-rennes1.fr*
[3] *Departamento de Geologia. Facultad de Ciencias Fisicas y Matematicas, Universidad de Chile, Casilla 10465 Correo21, Santiago, Chile, fherve@cec.uchile.cl*

Study of 53 dykes in a Miocene doleritic dyke swarm located above the subduction of the Pacific oceanic floor beneath Southern Patagonia (Chile), shows that the opening of the dykes cannot be related with the azimuth of subduction during the same period of time. However, if we consider: a/ the main fault directions, b/ the orientations of the dykes, c/ the existence of large dextral shear zones, d/ the azimuth of subduction of the Pacific floor at the time of the dykes emplacement, e/ the shape of the Taitao peninsula, f/ the macroscopic evidence of dextral and sinistral transtension, g/ the direction and age of the structures recognized in the Golfo de Penas and in the Cosmelli basin, a general kinematics model can be proposed. This model, based on a physical indentation experiment, characterized by a weak confinement on one of its edges, explains the origine of all these structures. Study of the shallow AMS tensors shows that the magnetic minerals located at the margins of many dykes witness an oblique opening and confirms the Miocene stress pattern. We postulate that the strong acceleration of the subduction which occurred at the time of the formation of all these structures, changed the dip of the subduction plane and dramatically modified the superficial stress. In Patagonia, this abrupt change in the dip of the subduction would have acted like a large indenter.

Study of the P' parameters across each dyke shows that most of the dykes display a higher value close to the continental walls of the dykes (Andean wall). We have also checked, for dextral and sinistral transtensional dykes if the location of the highest P' values was associated with a larger horizontal displacement of the terrain located on the Andean side. This hypothesis has been partly confirmed by the data. The rapid acceleration of the subduction which occurred during Miocene times explains both the indentation pattern, the formation of the Miocene dyke swarm, and why the Andean side of the dykes moved away from the oceanic border. The border facing the Andes has been obviously the most active, as shown by the larger number of prolate shapes on this side even if the oblate sites are generally dominating. These two criteria could be used to better understand the dip and the azimuth of past subductions.

Earthquake-induced clastic dikes detected by anisotropy of magnetic susceptibility

Tsafrir Levi[1,2,3], Ram Weinberger[2], Tahar Aïfa[4], Yehuda Eyal[1] and Shmuel Marco[5]

[1]*Department of Geological and Environmental Sciences, Ben Gurion University of the Negev, Beer Sheva, Israel, eyal@bgumail.bgu.ac.il*

[2]*Geological Survey of Israel, 30 Malkhe Israel Jerusalem, Israel, rami@geos.gsi.gov.il*

[3]*Ramon Science Center, Jacob Blaustein Institute for Desert Research, Ben-Gurion University of the Negev, Mitzpe Ramon, Israel, zafrir@bgumail.bgu.ac.il*

[4]*Géosciences-Rennes, CNRS UMR6118, Université de Rennes l, Campus de Beaulieu, Bat.15, Rennes cedex, France, tahar.aifa@univ-rennes1.fr*

[5]*Department of Geophysics and Planetary Sciences, Tel Aviv University, Tel Aviv, Israel, shmulik@terra.tau.ac.il*

Clastic dikes are sub-vertical sheets of sediment contained within a host rock resembling magmatic dikes. Clastic dikes may be formed either by passive deposition of clastic material into pre-existing fissures or by fracturing and injection of clastics during seismic shaking. While the final geometry of such structures is everywhere similar, inferring their mode of formation is commonly ambiguous. In order to distinguish between the two modes of formation, we developed a new application of the anisotropy of magnetic susceptibility (AMS) analysis, assuming that clastic dikes of different origins have different indicative magnetic fabrics. To better understand their emplacement mechanisms, we applied fracture mechanics criteria originally developed for magmatic dikes. We studied the mechanisms of clastic-dike formation within the seismically active Dead Sea pull-apart basin, where hundreds of clastic dikes cross-cut the late Pleistocene lake sediments of the Lisan Formation. They are typically up to 1,000 m long, 30 m high and 0.4 m wide and are arranged mainly in radial and tangential geometry. We show that passively-filled dikes, which contain brownish silt resembling local surface sediments, are characterized by oblate AMS ellipsoid and vertical principal eigenvector V3 directions. Dikes that contain green clayey sediment connected to mineralogically identical detrital layer of the Lisan Formation are characterized by triaxial AMS ellipsoid, well-grouped sub-horizontal and parallel to the dike walls V_1 directions, and sub-vertical V_2 directions. Field evidence and AMS analysis indicate that most of the dikes were emplaced by injection inferred to be due to seismically-triggered fluidization-liquefaction. This novel application of the AMS provides a petrofabric tool for distinguishing passively filled dikes from earthquake-induced injection dikes and for identifying the latter as seismites. The preset study also demonstrates how to use our understanding of magmatic dike emplacement to infer the mechanics of other discordant structures.

The Kopparnäs basalt dyke reveals a hotspot source for the 1.64 Ga bimodal rapakivi association of southern Finland?

Arto Luttinen[1] and Paula Kosunen[2]

[1]*Department of Geology, P.O. Box 64, 00014-University of Helsinki, Finland*
[2]*Institute of Seismology, P.O. Box 68, 00014-University of Helsinki, Finland*
arto.luttinen@helsinki.fi; paula.kosunen@helsinki.fi

The Kopparnäs basalt dyke is exposed over a distance of 2 km in the coast of the Gulf of Finland. The dyke is composed of numerous en echelon segments; the overall strike of the near vertical dyke is E-W. The maximum width of the generally lens-shaped segments is ca. 1.5 m. The Kopparnäs dyke cross-cuts various granitoids, gneisses, and gabbroids. Inclusions of wall-rock are fairly abundant and probably mainly represent dislocated bridges. Recent palaeomagnetic measurements (Satu Mertanen, personal communication, 2005) imply that the undated dyke is one of the wide-spread ~1.64 Ga mafic dykes (Häme swarm) which are associated with rapakivi magmatism in southern Finland. In fact, one of the minor rapakivi plutons is located only 5 km east of the Kopparnäs dyke. The Kopparnäs dyke is in mainly aphanitic and aphyric. Some wide segments have a porphyritic appearance due to weakly oriented plagioclase laths. Geochemically, the dyke is notably uniform and broadly similar to the dykes which belong to the Häme swarm, but it can be distinguished from them on the basis of unusually low SiO_2 (~45.6 wt.%) and high FeOtot (~17 wt.%) at MgO of ~4.8 wt.%. Although the dykes plot within the alkaline field in TAS diagram, normative hypersthene and olivine indicate an olivine tholeiitic affinity. Concentrations of incompatible elements, such as Nb (42 ppm) and TiO_2 (4.8 wt.%) are the highest so far reported for rapakivi-related magmas. High $(La/Sm)_N$ (2.4), $(Sm/Lu)_N$ (3.7), and $(Nb/La)_N$ values (0.7) produce a fairly smooth mantle-normalised incompatible element diagram that is not typical of the Häme swarm and resembles that of modern ocean island basalts (OIB). Preliminary Nd isotopic data show marginally negative initial epsilon Nd (1.64 Ga) values (~ -1) which are consistent with a hotspot source, but do not preclude crustal contamination. The geochemical OIB-affinities of the Kopparnäs dyke concur with models that associate the bimodal rapakivi suite of southern Finland with hotspot activity beneath the Mesoproterozoic continent.

Propagation of pressure-driven fractures with implication to dike-induced seismicity

Vladimir Lyakhovsky[1] and Ram Weinberger[1]

[1]*Geological Survey of Israel, 30 Malkhe Israel Jerusalem, Israel, vladi@geos.gsi.gov.il*

Seismological data support the interpretation that deflation of volcanoes is associated with lateral migration of magma from the caldera region and formation of dikes. The data include a time sequence of earthquakes of magnitude two and greater, but their origin is not well understood. We examine the host-rock deformation surrounding a pressure-driven fracture, with an emphasis on assessing the conditions require to produce seismicty. The host-rock deformation is governed by a damage rheology model that provides a quantitative treatment for macroscopic effects of evolving distributed fracturing with local crack density represented by a damage state variable. A thermodynamically-based equation for damage evolution accounts for degradation of rock elasticity, damage-strain localization in a narrow zone, transition between quasi-static to dynamic regime followed by a stress drop. The magnitude of the simulated seismic events is estimated using the moment-magnitude relation, where the seismic moment is calculated from the stress drop during the dynamic stage of damage growth. The relation between the rate of fracture process and material strength introduced in the model as dynamic weakening is responsible for the transition from the quasi-static to dynamic regime. The governing material properties are constrained by analyses of stress-strain and acoustic emission laboratory data during deformation leading to brittle failure of rocks.

In the present application of the damage rheology model, the shape and pressure distribution inside the fracture are coupled with the host-rock deformation. The rate of dike propagation and corresponding seismic activity is controlled by two different timescales. The magma-related timescale is associated with magma viscosity and pressure in the magma chamber. The damage-related timescale reflects the rate of the process zone growth. The model predicts two different regimes of dike propagation, i.e., damage-controlled with self-similar shape of the process zone, and magma controlled regime with a relatively narrow process zone around the dike. The presented model also describes the transition from the quasi-static damage-controlled regime to quasi-dynamic magma-controlled regime of dike propagation. Consequently, the model produces a migrating seismic activity in space and time that shows similarity to recorded dike-induced seismicity in Iceland, Hawaii and Japan.

Increasing enriched mantle component with time in Proterozoic mafic dyke swarms of the Ungava Peninsula, Canada

Charles Maurice[1], Don Francis[1] and Jean David[2]

[1]Earth and Planetary Sciences, McGill University, 3450 University St., Montréal, QC, H3A 2A7, Canada, cmaurice@eps.mcgill.ca, donf@eps.mcgill.ca
[2]GEOTOP-UQAM-McGill, CP 8888, Succ. Cemtre-Ville, Montréal, QC, H3C 3P8, Canada, k32460@er.uqam.ca

Recent regional mapping of the Northeastern Superior Province of Canada by government geological surveys has been used to produce a new compilation of Proterozoic mafic dykes in the Ungava Peninsula, including approximately 200 new dyke analyses covering ~70% of the area. The major element compositions of most of the dykes indicate that they represent tholeiitic liquids whose compositions are controlled by crystal fractionation along the gabbroic cotectic. However, a range of parental magmas compositions is required to account for the trace element variations. The dominant older (ca. 2.2 Ga*) dykes in the northern part of the Ungava Peninsula were emplaced coevally with rifting events that preceded the Trans-Hudson Orogeny. These dykes exhibit low La/Sm ratios, low Zr, and high PGE concentrations. Dykes with similar Zr and PGE systematics, but having anomalously high La/Sm ratios, have higher SiO_2 and lower Fe_2O_3 concentrations. The composition of these dykes resembles those of the Eskimo basalts of Belcher Islands (ca. 1.9 Ga*), which have been interpreted to be crustally contaminated (Legault et al., 1994).

Younger (ca. 2.0 Ga*) dykes outcrop predominantly in the South. They have variable Zr contents, low PGE concentrations and higher La/Sm ratios than the older syn-rifting dykes. These dykes are coeval with ca. 2.04-1.96 Ga (Parrish, 1989; Machado et al., 1993) continental basalts and alkaline lavas (Kenty Lake suite) of the Povungnituk Group to the North, and are geographically associated with continental basalts of similar age in the South (Richmond Gulf and Nastapoca groups; ≤ 2.03 and 1.90 Ga*), as well as alkaline lamprophyres and carbonatites (ca. 1.94 Ga; J. David, unpub. data).

Simple mixing between the composition of a low-Zr dyke and average Zr-rich Kenty Lake alkaline basalt reproduces the compositional spectrum of many of the younger dykes. This observation, coupled with their geographical association with alkaline lamprophyres and carbonatites, implies that the parental magmas of the dyke swarms contain variable amounts of an enriched mantle component. The secular evolution from Zr-poor to variably Zr-enriched tholeiitic magmas in the dykes of the Ungava Peninsula suggests the increasing incorporation of an enriched lithospheric mantle component with time.

* Ages as reported by Buchan and Ernst (2004) in their compilation map.

Paleo- and Mesoproterozoic dyke swarms at Lake Ladoga area, NW Russia – paleomagnetic studies

Satu Mertanen

Geological Survey of Finland, P.O. Box 96, FIN-02151 Espoo, Finland, satu.mertanen@gtk.fi

Paleomagnetic studies have been carried out on two mafic dyke swarms and on three dated Svecofennian 1.8 Ga post-collisional shoshonitic intrusions on the northwestern coast of Lake Ladoga in NW Russia. The NW-SE trending lamprophyre dykes as well as the genetically associated shoshonitic intrusions have, for the most part, preserved their primary thermoremanent magnetization, acquired at ca. 1.8 Ga. Thermal demagnetizations and rock magnetic studies imply that in both rock types the remanence resides in titanomagnetite. The shoshonitic intrusions show dual polarity while the lamprophyres show single polarity. In addition to the primary thermoremanence, the lamprophyre dykes and the shoshonitic intrusions carry another, secondary remanence direction that is isolated in lower unblocking temperatures and coercivities. One of the shoshonitic intrusions is totally remagnetized in this direction. Thermal demagnetizations and thermomagnetic analyses imply that the remagnetization resides both in titano-magnetite and titano-maghemite. Paleomagnetic poles of this secondary remanence are close to the known Fennoscandian key poles of the age of 1.63-1.54 Ga.

Another, NE-SW trending undated dyke swarm of fresh clinopyroxene dolerites was also studied. The dolerites show single remanence component isolated in high coercivities and unblocking temperatures, which according to rock magnetic studies resides in titanomagnetite. Paleomagnetic poles are in agreement with the 1.63-1.54 Ga key poles. Based on these ages, it is suggested that the dolerite dykes represent dyke magmatism that took place during the time between the emplacement of the Wiborg (1.65-1.63 Ga) and Salmi (1.55-1.53 Ga) rapakivi batholits. Emplacement of the dolerite dykes and rapakivi intrusions form a plausible source for the partial remagnetization of the 1.8 Ga old shoshonitic intrusions and lamprophyre dykes.

East-Carpathian mafic dikes – indicators for post-Variscan crustal extension

Marian Munteanu[1], Kadosa Balogh[2], Haino Uwe Kasper3

[1]*University of the Witwatersrand, Johannesburg, munteanum@geosciences.wits.ac.za*
[2]*ATOMKI Institute of the Hungarian Academy, Debrecen, balogh@atomki.hu*
[3]*Universität zu Köln, Köln, hu.kasper@uni-koeln.de*

Mafic dikes occur, isolated or grouped in swarms, throughout the metamorphic terranes of the Eastern Carpathians. Here we bring petrological, geochemical and geochronological evidence for the emplacement of these dikes during the extensional events that preceded the main Carpathian orogenic stage. The East-Carpathian mafic dikes (ECMD) can be divided in dolerites and lamprophyres. K-Ar data indicate Permian-Triassic ages (ca. 280-210 Ma) for the dolerites and Jurassic-early Cretaceous ages (180-135 Ma) for the lamprophyres. This suggests that (1) The doleritic dikes are related to the Meliata-Vardar rifting and ocean formation. This assumption is consistent with the ocean ridge-type composition of the dolerites. (2) The lamprophyric dikes are related to the Jurassic Civcin-Severin rifting event. The alkaline composition of the lamprophyric dikes and their intraplate geochemical features are arguments for the evolution of the Civcin-Severin extensional phase as a continental rift within the East-Carpathian segment. Chondrite-normalized REE values display flat patterns for dolerites (Lan/Ybn = 1.6-4.4) and steep ones (Lan/Ybn = 8.5-29) for lamprophyres. Earlier studies on both dolerites and lamprophyres (Dragusanu et al. 2000) suggested a depleted mantle source (143Nd/144Nd=0.51276-0.51298) and contamination with crustally derived Sr-rich fluids (87Sr/86Sr =0.7036-0.7157). Interaction with hydrous fluids is also evidenced by overgrowth of hornblende and biotite on pyroxene or olivine. ECMD show increased densities towards the Ditrau Massif, whose evolution also includes an initial mid-late Triassic mafic stage followed by a Jurassic alkaline one. Similar dikes occur in the Southern Carpathians, with the largest density within the Holbav-Sinca-Poiana Marului zone. Preliminary K-Ar datings on South-Carpathian dikes produced comparable ages, implying fairly synchronous dike emplacement along both the Southern and Eastern segments of the Carpathians. ECMD and their South Carpathian equivalents can be thus considered a mong the relatively few rifting-related magmatic rocks within the Alpine-Carpathian orogen.

Reference: Dragusanu, C., Shimizu, H., Tanaka, T., Munteanu, M., Takahashi, Y., Tanimizu, T. & Mihalache A., 2000, EOS, v. 81, no. 48, p. F1237

Magmatic flow in Permo-Carboniferous dolerite dykes of southern Sweden

Karsten Obst[1], William H. Owens[2], Donald W. Hutton[2], Norbert Nowaczyk[3]

[1]*Geologischer Dienst, LUNG M-V, Goldberger Str. 12, 18273 Güstrow, Germany*
[2]*Department of Earth Sciences, University of Birmingham, Birmingham B15 2TT, UK*
[3]*GeoForschungsZentrum Potsdam, Sektion 3.3, Telegrafenberg, D-14473 Potsdam, Germany*

Numerous magmatic dykes that occur at the south-western margin of the Fennoscandian Shield form a large braided dyke swarm converging towards the NW. Field studies indicate that the preferred orientation of the dykes changes from WNW–ESE in the north-western part of the dyke swarm to NW–SE in the south-eastern part. They often follow pre-existing fracture patterns in the crystalline basement and in the sedimentary bedrock. The dykes in southern Sweden, together with contemporaneously intruded dykes in Scotland and the Oslo region, are believed to be genetically related to a plume head associated with the attempted continental break-up of this area during the late Carboniferous to early Permian. Proposals have been made for a sourcing plume head in either the Kattegat or to the north of Jutland (Ernst & Buchan 1997, Obst 1999). The idea of a plume head has been tested by determining the magma flow direction in the dyke swarm of southern Sweden using field-based methods and AMS (anisotropy of magnetic susceptibility). The AMS data obtained from 108 oriented dolerite samples by using an inductance bridge (AGICO KLY-3S) suggest that regional variations within the dyke swarm exist. The mean susceptibilities of the dolerite samples mostly vary between 30 and 80 x 10^{-3} (SI), as typical for such tholeiitic rocks. The orientation of kmax is in part parallel, in part perpendicular or oblique to the major strike direction of the dykes. This seems to be independent of the shape of the magnetic fabric. In some dykes only is kmax similarly orientated to large phenocrysts of plagioclase or other field determined directional indicators (e.g. cuspy-shape contacts), and can be interpreted to represent the flow direction. In other dykes, especially in the north-western part of the dyke swarm, the AMS fabric might also reflect sinistral tectonic shear that was active during dyke intrusion. Whether this is due to the rise of large volumes of mantle magmas in eastern central Jutland (Silkeborg Gravity High; e.g. Sandrin et al. 2004) or not, is difficult to answer.

The results of hysteresis measurements made on 64 samples imply that variations in the AMS data are not related to variations of magnetic grain size. Magnetite is the dominant magnetic phase and occurs mostly as pseudo-single-domain (PSD) grains.

Chemistry and isotopes in Precambrian mafic dikes: are they important samples of lithospheric or asthenospheric mantle?

P. Jonathan Patchett[1] and Ulf L. Söderlund[2]

[1]*Dept. of Geosciences, University of Arizona, Tucson AZ 85721, USA*
[2]*GeoBiosphere Science Center, Lund University, Sölvegatan 12, 22362 Lund, Sweden*

The apparent association of some continental dike/sill complexes with rifting events generates a need to demonstrate, from magma chemistry, what type of mantle source was involved in generating the magmas that penetrate the crust. Very different tectonic interpretations would arise for the cases of a deep-sourced mantle plume, passive upwelling of near-surface asthenosphere, or localized pressure-release melting of lithosphere. Before mantle sources can be addressed however, potential crustal contamination effects must be filtered out of the geochemical observations, and some approximation of the chemistry of a primary magma must be arrived at. Employment of samples from chilled margins or the centers of larger dikes are alone both unreliable ways to avoid crustal effects, because case studies have shown that contamination can occur both at the margins of intrusions by diffusive exchanges or country-rock melting and hybridization, and in the centers either by serial emplacement of more evolved and contaminated magmas, or by syn- and post-crystallization aqueous fluid movements. Methods for avoiding crustal effects have included use of nepheline-normative (rather than quartz-normative) mafic rocks, screening of samples to select least crustal isotope ratios such as Sr, Pb and O, and in Cenozoic magmas, focusing on basalts that carry mantle xenoliths. An additional problem with gabbros and dolerites, as opposed to basalts, is that migrations of the residual liquid as solidification proceeds can make the incompatible-element chemistry of individual samples unreliable as indicators of enrichments achieved during mantle melting.

Precambrian dike/sill provinces can be characterized as low to moderate in magma volumes compared to Phanerozoic continental flood basalts (CFB), assuming only minor volumes of volcanic flows removed by erosion. In cases where the geochemical ambiguities have apparently been overcome, they have Sr and Nd isotopic signatures comparable to CFB, with maximum epsilon Nd in the neighborhood of +2.5 at Proterozoic times. Literature has been divided as to whether these signatures make CFB and Precambrian dike/sill magmas comparable to supposedly plume-sourced Ocean Island Basalts (OIB), or whether they have more lithospheric geochemistry. In the case of most Precambrian dike/sill provinces, the low to moderate magma volumes limit the thermal arguments that can be mustered in favor of mantle plumes. In many cases, the presence of negative Nb and/or Ta anomalies probably rules out a pure plume source. Thus the chemistry of Precambrian dike/sill complexes can be used only in rare cases to infer mantle sources and their significance in continental tectonics and crust-lithosphere-asthenosphere relationships.

1.8 Ga mafic dyke swarms of central North China Craton and continental break-up

Peng Peng

Institute of Geology and Geophysics, Chinese Academy of Sciences
ppwj@pku.org.cn, pengpengwj@mail.igcas.ac.cn

The 1.8 Ga mafic dyke swarms, extending for about 1000 km with an area of over 100, 000 km2 across central North China Craton (NCC), are from a uniform tectonic setting. Individual dykes are up to 40 km long and 80 m wide, averaging about 10 km long and 15 m wide. They are mainly N-NW directed with a few E-W and N-NE-oriented ones, showing a geometry pattern related to the Xiong'er triple-rift opening at 1.8 Ga along the south margin NCC. They are gabbro to dolerite rocks, consisting of clinopyroxene, plagioclase, and accessory Fe-Ti oxides, olivine or quartz, biotite, apatite, and sometimes alkaline-feldspar. A highly fractionated series and another relatively primitive series are identified according to their differentiation degrees. The primitive series composes of two kinds of dykes. One characterized by distinctive depletion of high field strength elements (such as Nb, Ta, Zr, Hf) and large ion lithophile elements (such as Rb, Ba, La, Ce) enriched in the primitive mantle-normalized spidergram, while the other group with weak depletion and enrichment. The initial 87Sr/86Sr (t = 1.8 Ga) ratios of the first group are closely around 0.7048 and ε_{Nd} (t = 1.8 Ga) values from -4.91 to -5.51, while the other one is 0.70213 - 0.70296 and 1.32 - 2.15 for the initial 87Sr/86Sr and ε_{Nd}, respectively. We suggest multi-sources for the dykes. The highly fractionated series show geochemical affinities with Xiong'er volcanics and can also be classified into two groups according to their orientations. The N-NW-oriented group shows an iron-enriched and silica-poor trend, while the E-W-oriented group cuts the former and shows a silica-rich and iron-poor trend. The changing of the trends may be caused by a contamination-related oxygen fugacity increase in the magma chamber. A SHRIMP zircon U-Pb age of 1778 ± 3 Ma and a single grain dissolution zircon/baddeleyite U-Pb age of 1777 ± 26 Ma are obtained. The zircons and baddeleyites have 207Pb/206Pb ages of 1803 ± 7 to 1756 ± 9 Ma. We argue that the dykes could be the feeders of the Xiong'er volcanic edifice and plume-related, contributing to the break-up of the NCC from Columbia supercontinent at 1.8 Ga.

Key words: 1.8 Ga; Mafic dyke swarms; North China craton; Xiong'er volcanic edifice; Columbia supercontinent.

Antarctica - Kalahari reconstruction at 180 Ma – new paleomagnetic data

Piispa, E.J.[1], Pesonen, L.J.[1], Luttinen, A.V.[2]

[1]*Division of Geophysics, P.O. Box 64, FIN-00014 University of Helsinki, Finland*
[2]*Department of Geology, P.O. Box 64, FIN-00014 University of Helsinki, Finland*
elisa.piispa@helsinki.fi; lauri.pesonen@helsinki.fi; arto.luttinen@helsinki.fi

Although the fit of the Grunehogna (Antarctica) and Kalahari cratons in Gondwana has been reasonably well constrained by geological, isotope and geochemical data, their exact relative positions have never been tested paleomagnetically. The initial period of Gondwana breakup was characterized by voluminous mafic magmatism and lithospheric thinning at ~180 Ma, possibly due to a mantle plume beneath these cratons. The rapid emplacement of compositionally diverse flood basalts of the Karoo large igneous province was followed by intrusion of ultrapotassic dykes across the juxtaposed cratons at 160 – 120 Ma. Recent off-shore aeromagnetic data from Antarctica implicate final splitting of the craton during this period at ~140 Ma. Here we present new results of detailed paleomagnetic sampling of Karoo lavas and dykes from Vestfjella, Dronning Maud Land, Antarctica. The sample material represents various ~180 Ma flood basalts and younger dykes, including ~160 Ma ultrapotassic dykes. Our primary objective is to define the pre-breakup position of the Grunehogna craton relative to the Kalahari craton and to test a recently proposed, unconventional reconstruction of Jokat and his co-workers. Results from the new rock magnetic and petrophysical measurements, coupled with existing geochemical and isotope geochemical results enable us to construct a novel Antarctica – Kalahari reconstruction at 180 Ma. Our data from >900-m-thick lava suite in north Vestfjella demonstrate a reverse to normal magnetic stratigraphy in these lavas, which is consistent with previous data from the southern parts of Vestfjella. The petrophysical data suggest that the lower reverse polarity flows appear to be distinctly different from those of the upper normal polarity flows. We use the polarity data from seven sampled sections to constrain the regional lava stratigraphy in new detail and to evaluate the stratigraphical relationships between Antarctic and African parts of the Karoo province. Anisotropic magnetic susceptibility data help us to evaluate whether or not compositionally different magma types had distinctive eruptive systems as has been proposed in previous petrogenetic models.

Early-Middle Jurassic Mafic Dykes from Western Dronning Maud Land (Antarctica): Identifying Mantle Sources in the Karoo Large Igneous Province

T. R. Riley[1], P.T. Leat[1], M.L. Curtis[1], I.L. Millar[1] and A. Fazel[2]

[1] British Antarctic Survey, High Cross, Madingley Road, Cambridge CB3 0ET, UK; t.riley@bas.ac.uk, p.leat@bas.ac.uk, m.curtis@bas.ac.uk, ilm@bas.ac.uk
[2] Department of Earth Sciences, Open University, Milton Keynes, MK7 6AA, UK; A. Fazel@open.ac.uk

Dolerite dykes in the Ahlmannryggen region of western Dronning Maud Land (Antarctica) form part of the wider Karoo igneous province. The composition of the dykes provide the strongest geochemical evidence to date that the province was at least, in part, related to the arrival of a mantle plume. The dyke compositions extend the geochemical limits of the Karoo volcanic province and include low- and high-Ti magma types, which incorporate both picrites and ferropicrites. Provisional geochronology on the dykes indicate two Mesozoic age peaks at 178 Ma and 190 Ma. Proterozoic peaks have also been identified in the range 750 - 1100 Ma. Four chemical groups have been identified in the Ahlmannryggen region based on ~ 90 dykes and sills. The groups are defined on the basis of TiO_2 and Zr contents, but are reinforced by rare earth elements, $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$. Group 1 is interpreted to be largely Neoproterozoic in age, whilst groups 2 - 4 are Mesozoic. Group 1, low TiO_2-Zr dykes overlap in composition with the ~1000 Ma Borgmassivet Intrusives, with the exception of four dykes that are distinct to the other Proterozoic intrusive rocks and overlap with the low-Ti, Kirwanveggen lavas, which are Middle Jurassic in age. Group 2 rocks have moderate TiO_2-Zr contents and are interpreted to be the result of mixing between plume-derived melts and minor amounts of lithospheric mantle partial melt. Group 3 rocks form the most distinct magma group and are largely picritic with superficially MORB-like chemistry (high TiO_2, Zr, flat REE patterns, $^{87}Sr/^{86}Sri \sim 0.7035$, $e_{Nd}i \sim 9$). The Group 3 magmas are derived from deep-seated depleted mantle. The group includes several high Mg-Fe dykes (ferropicrites), which are interpreted as melts of Fe-rich streaks in a mantle plume starting head. Initial geochronology suggests that the ferropicrites are significantly older at 190 Ma than the main Karoo peak. Group 4 are the most enriched magma group with OIB-like chemistry and are dominated by picrites.

Kjakebeinet 159 Ma lamproites and their inclusions

K.R. Ilona Romu and Arto V. Luttinen

Department of Geology, P.O. Box 64, 00410-University of Helsinki, Finland
arto.luttinen@helsinki.fi, ilona.romu@helsinki.fi

A minor suite of N-S trending mica-rich (30-40 vol-%) dykes have been recently found from East Antarctica, western Dronning Maud Land, Kjakebeinet nunatak. They are c.1m wide and subvertical, contain crustal- and mantle-derived inclusions, and cross-cut Jurassic basalt lavas and dolerites. Preliminary research described these dykes as lamproites which are geochemically quite similar to Leucite Hills lamproites, USA. Based on 40Ar/39Ar dating of phlogopite, the 159 Ma dykes represent the youngest magmatic event so far identified in western Dronning Maud Land. Their age and paleogeographical location adjacent to southern Africa connect them to South African mica-rich kimberlites. These broadly similar rock types are distinguished based on minor mineralogical and geochemical differences. Compositional data for the lamproite dyke and its inclusions bring unique information about the character of the lithospheric mantle and crust below Dronning Maud Land. The well-rounded inclusions represent several rock types. Most of the 25 samples are crustal felsic gneisses, the compositions of which range from alkali feldspar granite to tonalite. Five samples are granular, intermediate rocks that are composed of bytownite plagioclase, diopside, and possible pseudomorphs after garnet. Two mafic clinopyroxenite samples consist of euhedral, partly melted, medium-grained diopside and interstitial ferro-pargasite. They may represent cumulates crystallised from alkaline mafic melt or metasome vein material from the lithosphere. A phlogopite-diopside-rock (glimmerite) consists of phenochrystal phlogopite and titan-bearing diopside. Two of the samples are sedimentary rocks that have been quite strongly altered, probably during the magmatic transport. A calcite-carbonatite (alvikite) inclusion shows O- and C-isotope compositions distinctive to mantle. Mostly zoned and titanoferous andratite garnet strengthens the impression of its magmatic origin. Given the frequent speculations on the petrogenetic association of lithospheric metasome veins, carbonatites, and lamprophyre clan rocks and the anomalous high abundance of carbonate (~15 vol. %) in the Kjakebeinet lamproites, it is possible that the pyroxenite, glimmerite, and alvikite inclusions represent source materials or comagmatic correlatives of the host lamproite.

Mesoproterozoic CFB magmatism in the Lake Ladoga basin, Russian Karelia

O.T. Rämö[1], I. Mänttäri[2], J. Kohonen[2], B.G.J. Upton[3], A.V. Luttinen[1], V. Lindqvist[1], V. Lobaev[4], M. Cuney[5] and L.P. Sviridenko[6]

[1]*Department of Geology, P.O. Box 64, FI-00014 University of Helsinki, Finland, tapani.ramo@helsinki.fi, arto.luttinen@helsinki.fi, viveca.lindqvist@helsinki.fi*
[2]*Geological Survey of Finland, P.O. Box 96, FI-02151, Espoo, Finland, irmeli.manttari@gtk.fi, jarmo.kohonen@gtk.fi*
[3]*Department of Geology and Geophysics, University of Edinburgh, Edinburgh EH9 3JW, U.K., brian.upton@ed.ac.uk*
[4]*VSEGEI, 74 Sredny pr., 199106, Saint-Petersburg, Russia, Vladimir_Lobaev@vsegei.ru, Vladimir.Lobaev@g2r.uhp-nancy.fr*
[5]*UMR CNRS 7566 G2R-CREGU, Université H. Poincaré, BP 239, 54506 Vandoeuvre, France, Michel.Cuney@g2r.uhp-nancy.fr*
[6]*Institute of Geology Karelian Research Centre, Russian Academy of Sciences, 185610 Petrozavodsk, Karelia, Russia, sv@krc.karelia.ru*

The south-central part of the Fennoscandian (or Baltic) shield in Sweden, Finland, and adjacent Russia experienced widespread continental flood basalt (CFB)-type basaltic magmatism (dykes, sills, lavas) and red-bed sedimentation in the Mesoproterozoic. U-Pb zircon/baddeleyite data indicate ages of ~1260 Ma and ~950 Ma for this magmatism in southwestern Finland and central Sweden. In the Lake Ladoga region, Russian Karelia, the Mesoproterozoic record registers the formation of a complex faulted-bounded basin, ~150 km in diameter, with intercalated sandstone, doleritic sills and dykes, and mafic lavas. The mafic subvolcanic rocks are exposed on islands and skerries in the northeastern part of the basin (Valaam, Mantsinsaari, and Lunkulansaari islands) and basaltic lavas (eleven flows with an average thickness of about 15 m) are intercalated with clastic (mostly arkosic) sandstones in a section revealed by deep drilling in the Salmi-Tulemajoki region.

In general, the Lake Ladoga dolerites and lavas are alkaline, relatively evolved, and strongly enriched in the light rare earth elements, Y, K, Rb, U, Th, Nb, Zr. The dolerites of the Valaam Island (and a gabbro from Lunkulansaari) have initial ε_{Nd} (at 1460 Ma) values between -9.6 and -8.6. This points to a Neoarchean, metasomatically enriched lithospheric mantle source. Preliminary Nd isotope data on the Tulemajoki basalts and basaltic cobbles on the coast of the Valaam Island have ε_{Nd} (at 1460 Ma) values of -5.8 to -4.1. These basalts may have been derived from a different source than the (more unradiogenic) subvolcanic mafic rocks. U-Pb baddeleyite data on a dolerite on the Valaam Island in the northwestern part of Lake Ladoga imply a crystallization age of 1457 ± 3 Ma. This shows that the Mesoproterozoic CFB magmatism in the southeastern Fennoscandian shield commenced at least ~200 Ma earlier than previously anticipated and thus very shortly after the emplacement of the classic, 1670–1530 Ma, rapakivi granites. The basin formation probably started during the emplacement of the extension-related rapakivi intrusions as a result of thermal contraction of the rift zones, and the relatively thin crust hosting the rapakivi granites permitted ascent of the mantle-derived basaltic magmas. Whether the generation of these CFBs was related to a mantle plume is yet to be determined. In stratigraphy, the Mesoproterozoic basalts of the Lake Ladoga basin belong to the lower

part of the basin and may represent basic volcanism that immediately followed the emplacement of the rapakivi intrusions.

Preliminary paleomagnetic, petrophysical and rock magnetic data from Valaam sill, Lake Ladoga, Russian Karelia

Salminen, J. and Pesonen, L.J.

University of Helsinki, P.O. Box 64, 00014 University of Helsinki, Finland
johanna.m.salminen@helsinki.fi

It has been proposed that Laurentia and Baltica remained intact more than 600 million years during 1.83 - 1.26 Ga forming the core of the supercontinent Hudsonland. To test this hypothesis paleomagnetic data are needed from this age interval from both continents. The Valaam sill in Lake Ladoga, Russian Karelia, is most suitable for this purpose since its new Pb-Pb age 1.46 Ga (Rämö et al., 2004) matches well with that of the St. Francois igneous rocks (1.47 Ga) of Laurentia (Meert et al., 2002), and because the sill is in its original nearly horizontal position. We present preliminary paleomagnetic, rock magnetic and petrophysical data of the Valaam gabbro-monzonite-syenite sill as based on 19 samples from various phases of the sill, collected during the 2003 and 2004 field seasons.

Petrophysical (density, susceptibility, NRM and Q-value) and rock magnetic properties (hysteresis and Curie-points) were measured in order to study the remanence stability, mineralogy and magnetic grain size. Density, susceptibility and NRM values of gabbro-monzonite are higher than in syenites. Moderate Q-values (gabbro-monzonites 0.51-2.31 and syenites ca. 1.24) suggest that the remanence is carried by large PSD grains. Hysteresis data also point to PSD grain sizes, close to MD area. The slightly irreversible thermomagnetic curves indicate that at least three magnetic phases (titanomagnetite, nearly pure magnetite and hematite) are present.

The sill carries a high coercivity remanent magnetization (preliminary data: D = 45.3°, I = -17.7°, k = 485.4; α_{95} = 3.5, 19 samples), which is regarded as primary, although no field test is yet available. The majority of the samples show also two low coercivity components. Earth's magnetic field, whereas the other one (D = 44.4°, I = 27.6° k = 76.4; α_{95} = 10.6, 13 samples) gives a paleomagnetic pole Plat = -33.7°, Plon = 156.0° (*dp* = 6.3° and *dm* = 11.6°) and suggests a Permian (?) overprint. The high coercivity component yields a paleomagnetic pole Plat = 11°, Plon = 165°, *dp* = 2°, *dm* = 4° (with a paleolatitude of 10°S of the shield) suggesting a magnetization age between Subjotnian (1.60 Ga) and Jotnian (1.27 Ga) as based on APWP of Baltica. We discuss of the implications of this result in terms of the Hudsonland supercontinent and the proposed proximity of Laurentia with Baltica at 1.46 Ga ago.

3-D Gravity Modeling of the Unexposed Feeder Dyke Intrusion within the Koillismaa Layered Igneous Complex, Finland

Heikki Salmirinne, Markku Iljina and Jouni Vuollo

Geological Survey of Finland, P.O. Box 77, FI-96101 Rovaniemi
email: heikki.salmirinne@gtk.fi, markku.iljina@gtk.fi, jouni.vuollo@gtk.fi

The Koillismaa Layered Igneous Complex (KLIC) in Finland belongs to the group of early Palaeoproterozoic 2.45 Ga old layered intrusions of the Fennoscandian shield. KLIC consist of two separate exposed intrusions. The eastern intrusion, called Näränkävaara, is thought to represent the exposed part of an extensive feeder intrusion while the Western Intrusion is a thinner lopolith although areally more extensive. Between western and eastern intrusions there exists the 55 km long strong positive regional gravity anomaly indicating an unexposed feeder dyke intrusion capped mainly by low-density Archaean gneisses and also conglomerates, metasomatic albite-quartz rocks and felsic metavolcanics. In aeromagnetic data there are both a positive long-wave anomaly resulted from the big and deep feeder dyke intrusion and also many magnetic anomalies due to magnetized mafic dykes. Some of these dykes existing on same Arhaean gneiss complex have also been isotopically dated to be c. 2.45 Ga in age.

Previous interpretation of the Bouguer gravity anomalies suggested that unexposed feeder dyke intrusion is about 2.5-5 km wide and that the depth of the upper surface is between 1 and 2 km below the present erosion surface. In this study 3D structure of the feeder dyke intrusion has been modelled and presented by discrete objects. The main aim has been to model the depth of the unexposed upper surface and the general distribution of the anomalous mass causing the Bouguer anomaly. The regional gravity data consists of dense regular network with four measurement points per square km. In addition to this regional survey, six profiles (measurement interval c. 20 m) across the feeder dyke intrusion were measured and used for modelling. The feeder intrusion has been modeled using polygonal bodies and plunging prisms also for comparison. Density contrast of 330 kg/m^3 was used. The depth of the upper surface varies between 840–1500 m for prism bodies and 500–1350 m for polygonal bodies respectively. Model constructed by polygonal bodies indicates that anomalous mass is thinner and distributed wider than in prism model. Narrower mafic dyke swarms encountered on the present erosion surface cannot explain the strong and long-wave Bouguer anomaly. However, there can be a genetical link between 2.45 Ga old dykes and feeder dyke intrusion.

Lamprophyres in north Ladoga region and eastern Finland, evience of mantle enrichment at 1.8 Ga

Alexey D. Shebanov and Olav Eklund

Department of geology, Turku university
FI-20014, Turku, Finland

A lamprophyre dyke swarm striking NW from the Northern Ladoga (Karelia) towards Juankoski area (Finland) can be traced for ca. 200 km. At Ladoga, the dykes contain megacrysts and xenoliths of variable origin. Most spectacular are mica macrocrysts with unusually high Ca- and Ba-contents contain TiO_2 up to 11% (- 1 a.f.u.). The micas have no rutile exolution lamellas, but lamellas of titanite formed as a result of the high initial Ca-content in the original Ca-Ba-Ti-rich brittle mica and, presumably, rather low $f O_2$. Abundant apaite and allanite inclusions do also occur in the resorbed mica flakes. Other indicative minerals are Sr-rich carbonates, Ba-Sr-rich feldspars, Cr-enriched diopsides with a high jadeite component and late-stage ceolites. Chemically, the dykes are shoshonitic to alkaline lamprophyres, they contain up to 4.7 % P_2O_5, 10800 ppm Ba, 6400 ppm Sr, and 1300 ppm Ce. CO_2 is between 2 and 3% and F between 0.5 and 1.1%. Multi-element diagrams show a pronounced positive anomaly for Ba and negative anomalies for Ta, Nb, Hf, Zr and Ti. Taken together, these preliminary results indicate a mineral paragenesis that originated from a Ba-, Sr, - CO_2- and P-enriched mantle. This type of mantle in the region has been indicated by geochemical data (Eklund et al., 1998). Mineralogical investigations presume early formed deep seated paragenesis representing fragments carried out from the enriched mantle source (Shebanov et al., 2004). Our results support previous investigations indicating the presense of a rather unique lithospheric mantle in Southern Finland and Northern Ladoga at the Svecofennian post-collisional period. This mantle source was formed at ca. 1.8 Ga, an age of the mantle enrichment recorded also in xenogenic component in kimberlites, Eastern Finland (Peltonen & Mänttäri, 2001). Northern Ladoga-Juankoski dyke swarm comprises lamprophyre - lamproite-kimberlite transitional rock types and hence may have a diamond potential.

Mesozoic mafic dykes in eastern Victoria, Australia - a possible markers of the early stages of Gondwana break-up

Alvar Soesoo

Institute of Geology, Tallinn University of Technology, Estonia Street 7, Tallinn, Estonia, alvar@gi.ee

The break-up of the Gondwana supercontinent has been preceded and accompanied by voluminous outpourings of continental flood basalts and other types of magmatism. Like other parts of the Gondwana supercontinent, southeastern Australia experienced Mesozoic magmatism preceding break-up of the continent. Magmatism in southeastern Australia was dominated by low-Ti, Ferrar-type basalts, but recent work has shown the presence of small volume alkali-rich mafic and felsic magmatism at the edge of the Ferrar province. Since the Freestone Creek area was located on the former southern edge of Gondwana continental flood basalt province, which had a peak of magmatic activity between 184 to 179 Ma, these dykes may provide a valuable information about an early stage of Jurassic magmatism. The 191.4 (+/- 3.9) Ma basaltic dykes of the Freestone Creek area in eastern Victoria are alkali-rich melts, often with K_2O/Na_2O ratios around unity. Initial $^{87}Sr/^{86}Sr$ ratios of the Freestone dykes are 0.7048-.07067, but the higher values are likely to have influenced by secondary alteration; initial $^{143}Nd/^{144}Nd$ ratios are 0.512427-0.512449. The primary magma to the Freestone basalts can be modelled by small degrees of partial melting of an enriched mantle source, with garnet and amphibole as residual minerals. The major element variation in the basaltic dyke suite can be explained by fractionation at different crustal levels; the trace element variation is dominated by variations in partial melting percentages in the mantle. Some of the felsic rocks may have formed by protracted fractional crystallisation of a basaltic precursor similar to the Freestone basalt.

Diverse Precambrian mafic dyke swarms, Bastar craton, Central India: evidence of a heterogeneous mantle source

R. Srivastava

Banaras Hindu University, rajeshgeolbhu@yahoo.com

The Archaean Bastar craton of central India comprises diverse mafic dyke swarms of early Precambrian age. The Bastar craton is rectangular in shape; three sides bounded by Godavari, Mahanadi, and Narmada-Son rifts and another side by the Eastern Ghats Mobile Belt. These rifts and associated lineaments are thought to be existed since the Archaean time. Distinctly three different mafic dyke swarms have been recognized from this Archaean craton. Two sets of mafic dyke swarms are sub-alkaline tholeiitic in nature, whereas the third dyke swarm is high-Si, low-Ti and high-Mg in nature and documented as boninite-norite mafic rocks. The two sets of sub-alkaline mafic dykes are emplaced during the Mesoarchaean and Paleoproterozoic (~1.9 Ga) times respectively, whereas third set (boninite-norite dyke swarm) is emplaced in Neoarchaean time. Emplacement ages of these mafic dyke swarms have been established on the basis of field relationships, available ages of granitoid and mafic rocks, stratigraphic association with different rocks, and petrological and geochemical characteristics. Boninite-norite characteristic observed in one set of dykes is confirmed from their typical chemical compositions. Two sets of sub-alkaline mafic dykes recognised as BD1 (older) and BD2 (younger) show distinctly different geochemical characteristics. The BD1 dykes are low Ti+Fe+HFSE and high-Mg olivine to quartz normative rocks, whereas the BD2 dykes are predominantly quartz normative with relatively high Ti+Fe+HFSE and low-Mg contents. Multi-element and rare-earth element patterns also corroborate this distinction; all the three dyke sets show different patterns suggesting different genetic history. On the basis of these distinguished geochemical characteristics and compatible-incompatible trace element modelling it is suggested that the two sub-alkaline swarms were derived from distinctly different tholeiitic basaltic magmas. The Mesoarchaean BD1 dykes were derived from ~15-20% batch melting of a depleted lherzolite mantle source; in contrast, the Paleoproterozoic BD2 dykes were derived from ~7-10% batch melting of a relatively enriched mantle source. A post Archaean increase in the thickness of metasomatised mantle lithosphere is the probable cause of mantle enrichment. On the other hand boninite-norite dykes are product of different pulses of high-Mg boninitic magma produced by ~20% melting of a refractory mantle source. Voluminous extraction of basaltic material during the Archaean time (BD1 phase) was probably the main cause for producing refractory lithosphere.

Baddeleyite U-Pb dates of Meso- and Neoproterozoic mafic dykes and sills in the Baltic Shield

Ulf Söderlund[1,a], Clark E. Isachsen[1], Göran Bylund[2], Larry M. Heaman[3], P. Jonathan Patchett[1], Jeff D. Vervoort[4] and Ulf B. Andersson[5]

[1]Dept. of Geosciences, University of Arizona, Tucson, AZ 85721, USA
[2]Dept. of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden
[3]Dept. of Earth and Atmospheric Sci., University of Alberta, Edmonton, AB T6G 2E3 , Canada
[4]Dept. of Geology, Washington State University, Pullman, OR 99164, USA
[5]Inst. of Earth Sciences, Uppsala University, Norbyvägen 18B, SE-752 36 Uppsala, Sweden
[a]Present address: Dept. of Geology, Lund University, Sölvegatan 12, SE-223 62 Lund, Sweden, e-mail address ulf.soderlund@geol.lu.se

The Palaeoproterozoic (1.90-1.65 Ga) crust of central Baltica was intruded repeatedly by dolerite dikes and sills during the Meso- and Neoproterozoic times. We report 16 baddeleyite U-Pb dates for six generations of dolerites (in Ma):

Blekinge-Dalarna dolerites	946-970
Protogine Zone dolerites	1215-1221
Central Swedish Dolerite Group	1264-1271
Dalarna (a.k.a Tuna) dolerites	1461-1462
Värmland dolerites	~1568
Breven-Hällefors dolerites	~1595

The favoured tectonic model implies that the majority of these suites were related to subduction beneath a N-S directed active margin located somewhere west of the Baltic Shield. Dolerite intrusion is interpreted to reflect discrete events of extension as the arc retreated oceanward. Initial Hf and Nd isotope compositions give sub-horizontal evolution lines of $\varepsilon_{Hf} = +3.5$ and $\varepsilon_{Nd} = +1.3$ in epsilon vs. age diagrams between 1.6 and 0.95 Ga. Repeated recycling of older sediments (dominated by material with short residence ages) in a subduction system may have been a very efficient tectonic process for the production of a geochemically and istopically homogenous lithospheric mantle, and is also attractive for explaining the moderately depleted Hf and Nd signatures of the dolerites relative to CHUR reference values.

U-Pb, Sm-Nd, Lu-Hf chronology of a Mesoproterozoic meta-dolerite suite in SW Sweden – the use of Hf isotopes for P-T-t constraints during metamorphism

U. Söderlund[1], F.A. Hellström[2,3], I. Lundqvist[3] and P. J. Patchett[4]

[1]*GeoBiosphere Sci. Center, Lund University, Sölvegatan 12, 223 62 Lund, Sweden*
[2]*Department of Earth Sciences Geology, Box 460, 405 30 Göteborg*
[3]*Geological Survey of Sweden, Guldhedsgatan 5A, 405 30 Göteborg, Sweden*
[4]*Dept. of Geosciences, University of Arizona, Tucson AZ 85721, USA*

Two meta-dolerites in SW Sweden were investigated by U-Pb, Sm-Nd and Lu-Hf isotope systematics. The dolerites occur in the Western Segment of the Sveconorwegian orogen, which is assumed to be the continuation of the Grenville belt in Canada. The dolerite suite was emplaced at ~1300 Ma, constrained from U-Pb analyses of preserved baddeleyite grains in the Lunden dolerite. Both the Lunden and the Haregården dikes are metamorphosed at high grade but vary in both mineralogy and textures, and P-T data indicate metamorphism at different conditions. The Lunden dike has coronas of garnet and sodium rich augite (X_{Jd} = 0.11-0.21) that formed during high-pressure granulite metamorphism at ~13 kbar and 750-800°C. The age of saccharoidal zircon replacing baddeleyite is 1046 ± 4 Ma. Identical Hf isotope compositions of saccharoidal zircon and baddeleyite demonstrate that zircon inherited all its hafnium from baddeleyite, i.e. growth of zircon must have occurred before Hf equilibrated with other metamorphic minerals. The high-pressure granulite facies assemblage of the Haregården dolerite, on the other hand, equilibrated completely at about 9-10 kbar and 700-740°C. The Hf isotope composition of secondary zircons in this sample infers growth of zircon after isotopic equilibrium between main mineral phases was achieved. The Lu-Hf mineral isochron age of 1027 ± 8 Ma is identical with the Sm-Nd result of 1022 ± 28 Ma performed on the same mineral separates. The fadvoured interpretation is that both dikes record metamorphism during decompression. The results of this study show that U-Pb chronology combined with Hf isotope analysis of baddeleyite and morphologically different zircons offers an approach for correlating radiometric ages to specific metamorphic stages.

Asthenospheric signature in the Mesoproterozoic mantle below the SW Amazonian Craton: inferences from Nd-Sr compositions of mafic dikes and tectonic setting

W. Teixeira[1], J. S. Bettencourt[1], G. J. Rizzotto[2]

[1]University of São Paulo, Institute of Geosciences, Brazil
[2]Brazilian Geol. Survey
wteixeir@usp.br

The SW Amazonian Craton embraces the RNJP-Rio Negro/Juruena (1.80-1.55 Ga), RSIP-Rondonian/San Ignácio (1.55-1.30 Ga) and SAP-Sunsás/Aguapeí (1.25-1.00 Ga) provinces, which comprises distinct domains, resulting from accretionary orogens and intraoceanic subduction zones. Therefore this framework allows correlation with those of Baltica and Eastern Laurentia during the Mesoproterozoic time interval. $^{40}Ar/^{39}Ar$ (biotite, amphibole), U/Pb zircon and Nd-Sr whole rock analyses were performed on mafic rocks from three different lithologic markers related to some of the main stages of such a multi-arc system. The results were used to infer the mantle-derived melt composition throughout the Mesoproterozoic, and also to constrain the tectonic environment, as follows:

1) Serra da Providência Intrusive Suite (gabbro-charnockite-mangerite-granite; U/Pb ages between 1606-1532 Ma): comprises the oldest anorogenic magmatism within the RNJP. Mafic dikes from this suite (Roosevelt and Jamari domains) have $^{40}Ar/^{39}Ar$ ages between 1.51 – 1.58 Ga, whereas the Nd-Sr signatures are compatible with a depleted mantle source with very minor crustal contamination. Tectonically, these data fit the within-plate magmatic model; 2) Colorado Metamorphic Suite (ocean floor-like mafic/ultramafics, supracrustal rocks, and later bimodal plutonism): makes up the bulk of the crust in the southeasterly sector of the RSIP, partly overprinted by the SAP events. Amphibolites from this suite have $^{40}Ar/^{39}Ar$ ages in the range of 1.36 - 1.30 Ga, comparable with the age of the coeval orthogneisses (ε_{Ndt} = +4.1). Moreover, a cumulate meta-gabbro of this suite yields U-Pb zircon crystallization age of 1352 +4/-3 Ma. The scenario supports thereby the idea of a new accretionary orogen in the RSIP, in agreement with the Nd-Sr depleted-mantle signature of such mafic rocks; and 3) Nova Brasilândia Sequence (1.12-1.00 Ga): fills one of the rift-basins related to the SAP. It comprises metasedimentary sequences which overlie the Colorado Metamorphic Suite, and bimodal metaplutonic rocks. Mafic dikes of the Nova Brasilândia sequence show $^{40}Ar/^{39}Ar$ ages between 1.11 – 1.00 Ga, and have Nd-Sr signatures consistent with sources derived from partial melting in the upper mantle with minor components of the lower continental crust. As a whole, the predominant depleted-like isotopic signatures of the investigated mafic rocks reinforce the important role of successive soft-collision events and primary characteristics of the Mesoproterozoic crust in the SW Amazonian Craton.

Basic dike belts of the Vilyui paleorift (Siberian platform)

Mikhail Tomshin[1] and Konstantin Konstantinov[2]

[1] Diamond and Precious Metal Geology Institute, Siberian Branch, Russian Academy of Sciences, geo@yakutia.ru
[2] Diamond Mining Company ALROSA Co. Ltd, Russia

Geodynamic environment in which Middle Paleozoic magmatism and rifting occurred in the eastern Siberian craton was controlled by the plume-lithosphere interaction. Petromagnetic, magnetic-mineralogical and paleomagnetic studies of the basites made it possible to reconstruct paleomagnetic directions of the natural remanent magnetization (NRM) at the moment of the emplacement of the basites. The NRM vectors were found to differ noticeably in inclination. We interpret the differences as a result of the clockwise rotation of the Aldan block relative to the Aldan-Anabar one. We suppose the rotation was caused by the plume-lithosphere interaction and resulted in the formation of grabens in the eastern margin of the Siberian platform, which later developed into rift valleys such as Vilyui, Sobopol and Olenek. Ascent of the plume matter was accompanied by decompressional melting and formation of large volumes of basaltic magmas. The basic magmatism related to rifting processes was most active in the Vilyui paleorift. Two extensive (up to 700 km) dike belts were formed on the sides of the paleorift - the Vilyui-Markha (VMB) in the northwest and the Chara-Sinsk (CSB) in the southeast. Judging from the differences in inclination of the NRM vector groupings of basites, rifting encompassed a large period of time, from 420 to 320 Ma. Isotopic (Ar-Ar, Rb-Sr, Sm-Nd) studies of the basites showed they were emplaced during the same time interval. Formation of the dike belts occurred in pulses. Within the CSB the intervals between the magma emplacement pulses were short and within the main stage of the magmatic activity (380-370 Ma). Multiple dikes (dike-in-dike type) were formed with compositions ranging from gabbro-dolerites to syenites. Contrastingly, the intervals between the basic melt emplacement stages were longer in the VMB. The main magmatic activity that produced the VMB also occurred within the time interval of 380-370 Ma. Later on, at 360 Ma emplacement of kimberlites occurred in the Nakyn and Malaya-Botuobiya regions. In some areas of the VMB the magmatic activity ended in Early Carboniferous time (340-320 Ma). Some older isotope ages (440-420 Ma) were obtained for the rocks containing a significant amount of protocrystalline minerals. Formation of these rocks and minerals was found to have been related to the fractionation of the basic magma in a deep intermediate chamber that probably originated immediately after the separation of the melt from the protolith.

Fennoscandian dyke swarms CD-ROM and map

Jouni Vuollo and Heikki Salmirinne

Geological Survey of Finland, P.O. Box77, FIN-96101 Rovanie*mi, Finland, jouni.vuollo@gsf.fi*

This database development has originated in the framework of the finished project financed by Academy of Finland and later continued at the Geological Survey of Finland (GTK). We will publish the first edition (demo) of the Fennoscandian dyke swarm CD-ROM and the completed version is coming along with an IDC5 proceeding publication. This completed version will also include new data published in the IDC5 abstract volume. The aim of the CD-ROM data is to give a clear picture of the spatial and temporal distribution of mafic dyke swarms, their geochemical characteristics, geochronology and relationship to ore critical magmatic events.

The first GIS database (the Global Mafic Dyke GIS Database) was produced in Ottawa, Canada, funded by LITHOPROBE Canada and included information on more than 300 dyke swarms, ≈30 mantle plumes and isotopic ages. An updated dyke swarm map of northern North America and Greenland has been published by Buchan and Ernst (2004). The ongoing "Large Igneous Provinces in Time and Space" project will update this Global Dyke Swarm map (Ernst and Buchan, 2005) and the Fennoscandian database will be a part of this compilation.

In 1997 we started to build up the "Eastern Fennoscandian Mafic Dyke swarms GIS Databases" to collect all available geoscientific data for GIS purposes. Data have been collected in co-operation with State Company "Mineral", St. Petersburg, Geological Institutes; Karelian Research Center, RAS, Petrozavodsk, and the Kola Science Centre, RAS, Apatity, Russia. The dyke swarm data from Sweden and Norway will be included from a 1:2000000 Geological map database (Koistinen et al. 2001).

This CD-ROM DEMO contains much of the available data on dyke swarms and is gathered into a GIS system (ArcInfo-ArcView) to help combine and correlate the information. The databases include both vector and raster spatial data and a large amount of attribute data. All 192 of the 1:100 000-scale Finnish geological bedrock maps have been digitized (for dykes), and so have many detailed maps. The observation point database (GTK obs. point and Drill databases and University projects) includes 23881 points in both Finland and Russia, while the petrophysical database extracted from the national database of the GTK consists of 4627 observation points. There is also a geochronological database that includes more than 60 U-Pb and 20 Sm-Nd age determinations for diabases of different types and ages all over the area. The geochemical database consists of more than 1500 whole-rock analyses and numerous REE and PGE analyses. A totally updated Eastern Fennoscandian dyke swarm map (area of Finland) has been digitized (1:50 000) with the aid of all these databases and generalized 1: 2000000 maps will be published together with an IDC5 proceeding publication. We will demonstrate how these databases are created and how the maps presented here have been produced from the resulting data.

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List of Conference participants

Name	Organisation	Country
Prof. Sulaiman Alaabed	UAE University	U.A.E.
Dr. Andrei Arzamastsev	Geological Institute of the Kola Science Centre RAS	Russia
Dr. Wouter Bleeker	Geological Survey of Canada	Canada
Prof. José Moacyr Coutinho	Universidade de São Paulo	Brazil
Dr. Michael Curtis	British Antarctic Survey	United Kingdom
Dr. Alexandre de Oliveira Chaves	Comissão Nacional de Energia Nuclear (CNEN)	Brazil
Prof. Alex Deutsch	University of Muenster	Germany
Prof. Olav Eklund	Turku University	Finland
Prof. Sten-Åke Elming	Luleå University of Technology	Sweden
Dr. Richard Ernst	Geological Survey of Canada	Canada
Dr. David Evans	Albidon Ltd.	United Kingdom
Mr. Ian Fieldhouse	Inco	Canada
Dr. Nobuo Geshi	AIST, Geological Survey of Japan	Japan
Dr. Stuart Graham	University of Oslo	Norway
Dr. Jens Carsten Grimmer	University of Heidelberg	Germany
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Prof. James Head	Brown University	USA
Dr. Hannu Huhma	Geological Survey of Finland	Finland
Dr. Martin Klausen	University of Witwaterstrand	South Africa
Dr. Konstantin Konstantinov	Diamond Mining Company ALROSA Co. Ltd	Russia
Mr. Juha V. Korhonen	Geological Survey of Finland	Finland
Dr. Philip Leat	British Antarctic Survey	United Kingdom
Prof. Jean-Pierre Lefort	Géosciences-Rennes	France
Dr. Arto Luttinen	University of Helsinki	Finland
Dr. Vladimir Lyakhovsky	Geological Survey of Israel	Israel
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Dr. Satu Mertanen	Geological Survey of Finland	Finland
Dr. Marian Munteanu	University of the Witwatersrand	South Africa
Dr. Karsten Obst	LUNG MV	Germany
Prof. Jonathan Patchett	University of Arizona	USA
Dr. Peng Peng	Chinese Academy of Sciences	China
Prof. Lauri Pesonen	University of Helsinki	Finland
Ms. Elisa Johanna Piispa	University of Helsinki	Finland
Dr. Teal Riley	British Antarctic Survey	United Kingdom
Ms. Ilona Romu	University of Helsinki	Finland
Prof. Tapani Rämö	University of Helsinki	Finland
Ms. Johanna Salminen	University of Helsinki	Finland
Mr. Heikki Salmirinne	Geological Survey of Finland	Finland
Mr. Eero Sandgren	Geological Survey of Finland	Finland
Mr. Alexey Shebanov	University of Turku	Finland
Dr. Alvar Soesoo	Tallinn University of Technology	Estonia
Dr. Rajesh Srivastava	Banaras Hindu University	India
Dr. Ulf Söderlund	Lund University	Sweden
Prof. Wilson Teixeira	University of São Paulo	Brazil
Dr. Ram Weinberger	Geological Survey of Israel	Israel
Dr. Jouni Vuollo	Geological Survey of Finland	Finland
Dr. Saku Vuori	Geological Survey of Finland	Finland