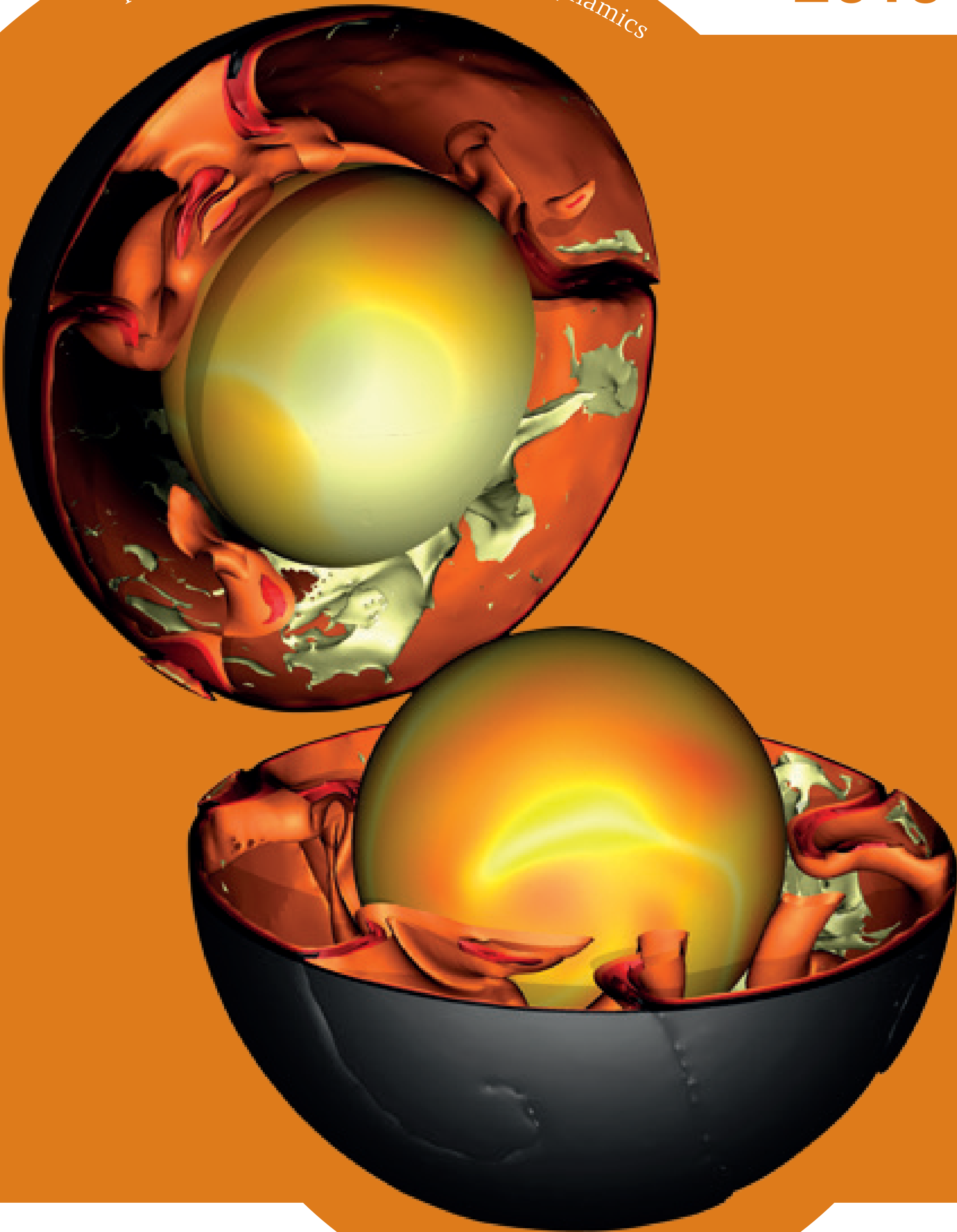
Annual Report

The Centre for Earth Evolution and Dynamics

2016



UiO : The Centre for Earth Evolution and Dynamics
University of Oslo

Front cover: *Dynamically self-consistent global model of mantle convection with single-sided subduction (dark red) recycling plates from the surface (black) into the mantle and hot material rising from the core-mantle boundary (yellow) in form of mantle plumes back to the surface. Model and image by Dr. Fabio Crameri, CEED.*

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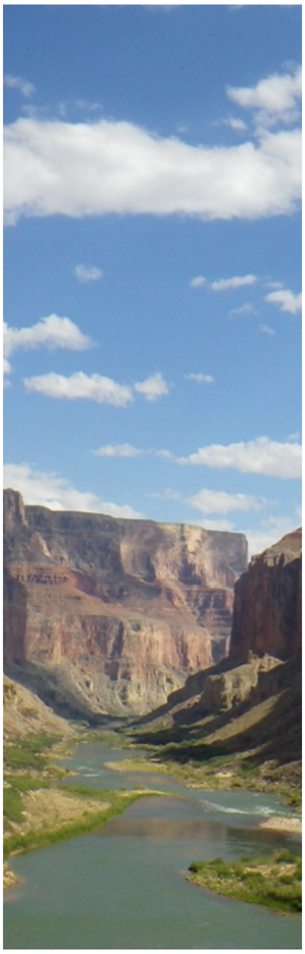
Index



From the Director

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Life and work at CEED is intense and extremely rewarding.

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Being part of the fourth revolution in Earth Sciences

The road towards establishing a centre of excellence in Norway, as elsewhere, is long and laborious, but the journey is worthwhile. On a sunny summer day in February 2005 I left Sydney, Australia, and headed 16000 km north, changing hemispheres and continents, to reach one of the northernmost academic cities, Trondheim, in Norway. It was a harsh winter in Norway, but that was the place where the dawn of a new revolution in Earth sciences began, and I wanted to be part of that incredible journey.

CEED started as a dream more than 14 years ago – two passionate and ambitious geologists, Trond H. Torsvik and Arne Bjørlykke made plans to establish a group dedicated to the most fundamental questions related to our planet at the Geological Survey of Norway (NGU). Bjørlykke, NGU's Director, planted CEED's seed by facilitating the formation of a new, unusual group for a geological survey, to be named the "Centre for Geodynamics", under the leadership of T.H. Torsvik.

It was a beginning of a new era for geosciences: Burke and Torsvik just discovered the source of the utmost powerful volcanism on Earth – the culprit of Large Igneous Provinces that repeatedly distorted Earth's surface environment. The incredibly potent, hot mantle plumes that transformed large parts of our planet in just a few thousand years by intruding and covering the crust with magmatic material, are presumably sourced from certain regions at the core-mantle boundary (CMB), 2800 km away from Earth's surface. Seismologists identified large domains of dense and hotter mantle, now called LLSVPs (Large Low Shear-wave Velocity Provinces), or Plume Generation Zones, at CMB several decades ago, but only when complex plate tectonic history was linked to the present day location of the LLSVPs, the connection between deep Earth and the surface became evident.

In 2013, almost a decade after Burke and Torsvik's finding, the Centre for Earth Evolution and Dynamics-CEED CoE, was awarded to Torsvik and colleagues at the University of Oslo, Norway. CEED (Torsvik) received an additional grant from the Research Council of Norway (RCN) for establishing a new national facility: the Giæver geomagnetic laboratory. In 2016 this laboratory was officially inaugurated at CEED and baptised by the Nobel Prize winner Ivar Giæver, the Norwegian discoverer of the tunnelling phenomena in superconductors.

In the first three years, under Torsvik's leadership, CEED blossomed, with the number of centre personnel almost doubled, as many enthusiastic researchers and students have joined its founders. Two years into its activity, CEED was also successful in attracting funds from RCN to establish a new geoscience graduate school, DEEP, which is a national platform for education and research in the Dynamics and Evolution of Earth and Planets. Now, four years after we began as a centre of excellence, there are more than 70 researchers at CEED, including 13 PhD students and 19 postdoctoral fellows, who are trained to be the next generation of geoscientists.

Life and work at CEED is intense and extremely rewarding. For the last four years we have advanced our knowledge of the deep Earth and its connections to the surface, proposing that the large-scale structure above the core-mantle boundary has barely changed, at least for the last 540 million years; we have discovered a "lost continent" – Mauritia; have detected continental crust under one of the largest volcanic islands: Iceland; and have drilled in Svalbard to uncover the causes for the biggest mass extinction on Earth that happened 252 million years ago.

CEED scientists published their research in more than 350 peer-reviewed papers, and 700 conference abstracts. 14 papers were published in high-impact journals, including Nature, Science and PNAS. Cambridge University Press opened its 2017 publishing season with an exquisite holistic scientific book: "Earth History and Paleogeography" by Torsvik and Cocks.

We continue to have big dreams and to ask difficult questions: Was plate tectonics different at times preceding the Phanerozoic (before 540 million years ago)? How is Earth's climate responding to True Polar Wander? What is Earth's water cycle and how is it linked to plate tectonics and mantle dynamics? What are the ingredients for planets' habitability?

Seventy scientists from 20 countries spanning 6 continents are working under CEED auspices to unravel the intricate histories of Earth and other planets and get closer to fulfil our centre's vision by answering fundamental questions.

Carmen Gaina

Contributors to the 2016 CEED report are:
M. Mansour Abdelmalak, Torgeir B. Andersen, Clint Conrad, Matthew Domeier, Pavel V. Doubrovine, Trine-Lise Gørbitz, Morgan Jones, Grace E. Shephard, Henrik H. Svensen, Trond H. Torsvik, Reidar G. Trønnes, and Stephanie C. Werner.

The report was compiled and coordinated by Carmen Gaina.

Special thanks to Trond H. Torsvik and Reidar G. Trønnes for diligently reading through numerous drafts.

Highlights from the first four years

Publications (CEED author names underlined)

1. Frieling, J.; Svensen, H.; Planke, S; Cramwinckel, Margot J; Selnes, Haavard, Sluijs, Appy, **2016**. Thermogenic methane release as a cause for the long duration of the PETM. ***Proceedings of the National Academy of Sciences of the United States of America.*** ISSN 0027-8424. 113(43), s 12059- 12064.

2. Torsvik, T. H., Amundsen, H.E.F., Trønnes, R.G., Doubrovine, P., Gaina, C., Kusznir, N.J.; Steinberger, B., Corfu, F., Ashwal, L.D.; Griffin, W.L., Werner, S.C; Jamtveit, B. **2015**. Continental crust beneath southeast Iceland. ***Proceedings of the National Academy of Sciences of the United States of America.*** ISSN 0027-8424. 112(15), s E1818- E1827.

3. Torsvik, T.H., Van Der Voo, R., Doubrovine, P.V., Burke, K., Steinberger, B., Ashwal, L.D., Trønnes, R.G., Webb, S.J., Bull, A.L. **2014**. Deep mantle structure as a reference frame for movements in and on the Earth. ***Proceedings of the National Academy of Sciences of the United States of America,*** 111, 8735-8740.

4. Werner, S.C., Ody, A., Poulet, F. 2014. The source crater of martian shergottite meteorites. ***Science***, 343, 1343-1346.

5. Torsvik, T.H., Amundsen, H., Hartz, E.H., Corfu, F., Kusznir, N., Gaina, C., Doubrovine, P., Steinberger, B., Ashwal, L.D., Jamtveit, B. **2013**. A Precambrian microcontinent in the Indian Ocean. ***Nature Geoscience,*** 6, 223-227.

Books

1. Torsvik, T.H., and Cocks, L.R.M. **2017**. Earth History and Palaeogeography. Cambridge University Press, 317 pp. ISBN 978-1-107-10532-4.

Prizes

1. The Geological Society of Norway **2017 REUSCH MEDAL** for **A. Minakov**
2. The University of Oslo **2016 RESEARCH PRIZE** for **T.H. Torsvik**
3. The European Union of Geosciences **2016 ARTHUR HOLMES MEDAL** and HONORARY MEMBER for **T.H. Torsvik**
4. The European Union of Geosciences **2016 ARNE RICHTER** Early Career Scientist **PRIZE** for **G.E. Shephard**
5. The German Geological Society **2015 LEOPOLD VON BUCH MEDAL** for **T.H. Torsvik**
6. The Geological Society of Norway **2015 TOFFEN PRIZE (outreach) for H.H. Svensen**

Major Conferences arranged

1. The PGP-CEED Kongsberg seminar Earth Evolution and Dynamics, May 2013, Kongsberg, Norway. Organizing committee: Jamtveit and Gaina, ca. 50 participants

2. The 13th International Workshop on Modelling of Mantle and Lithosphere Dynamics, August 31 – September 5, 2013, Hønefoss, Norway. Organizing committee: Torsvik, Werner, Buiter, Doubrovine, Bull-Aller, 96 registered participants

3. The 7th Nordic Supercontinent Workshop, October 13-19, 2014, Haraldvangen, Norway. Organizing committee: Torsvik, Domeier, Doubrovine, Hansma, ca. 30 participants.

4. **The CEED Wilson Lectures**
   CEED is organising every year a public lecture at the University of Oslo with distinguished international scientists on topics closely related to CEED core activities

   2014 Linda Elkins-Tanton (School of Earth and Space Science at Arizona State University): The evolution of terrestrial planets and the relationships between Earth and life on Earth

   2015 Øyvind Hammer (Naturhistorisk museum): Tidsdypet under våre føtter (in Norwegian)

   2016 Anne Hope Jahren: 30 Things That Everyone Should Know About Global Change

Organisation chart of the centre

According to the original proposal, CEED activities were initially carried out in five thematic research framework:

Theme 1: Deep Earth: Materials, Structure and Dynamics (R. Trønnes)
Theme 2: Dynamic Earth: Plate motions and Earth history (C. Gaina)
Theme 3: Earth Crises: LIPs, mass extinctions and environmental changes (H. Svensen)
Theme 4: Earth and Beyond: Comparative Planetology (S.C. Werner)
Theme 5: Virtual Earth: Numerical models of Earth Dynamics (M. Dabrowski/A. Bull-Aller).

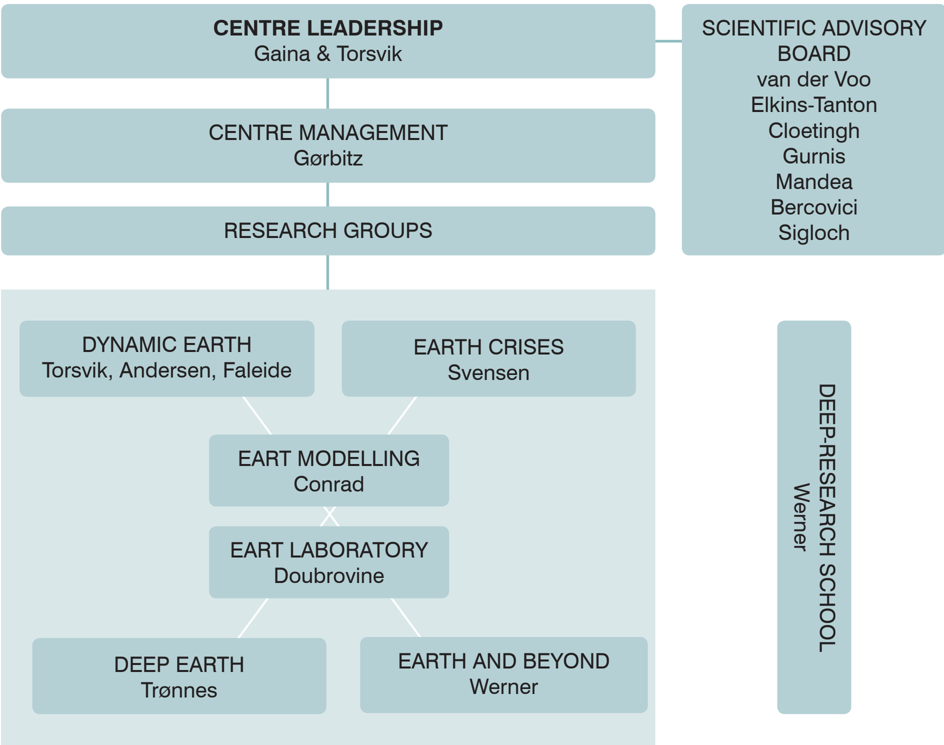
Although part of the original proposal, M. Dabrowski changed his UiO employment to 50% before CEED started. CEED decided to assign the leadership of the "Virtual Earth" group to the postdoctoral fellow A. Bull-Aller, who is trained as a geodynamicist/numerical modeller and had a 100% position when CEED started. The name of the "Virtual Earth" group has been changed to "Earth Modelling", and from 2016 this group is headed by C. Conrad.

A separate administrative group, led by T-L. Gorbitz, is in charge of personnel and administrative-related tasks.

From 2014, CEED is hosting the Ivar Giæver Geomagnetic Laboratory, a Norwegian national research infrastructure for paleomagnetism and rock magnetism. A sixth research group, the "Earth Laboratory", has been established in order to take care of the activities linked to the national geomagnetic laboratory.

Since 2016 CEED is also hosting the National Research School DEEP - Dynamics and Evolution of Earth and Planets.

The organisational chart of the centre is presented below



The centre board

CEED has not appointed a separate board; as a part of the Department for Geosciences, it has the same board as the host institute. From 2013 to 2017 the Department of Geosciences board members were: B.L. Skjelkvåle (Head of Department), A. Myhre (Deputy Head of Department), three academic members representatives (C. Gaina, L.Talaksen and J. E. Kristjánsson), one administrative/technical members representative (M. Heeremans), one temporary staff representative (elected each year), two student representatives (elected each year) and one external member (G. Gunleiksrud Haatvedt, Det Norske oljeselskap).

Scientific Advisory Committee

A number of distinguished scientists has been listed in the original SFF proposal as members of CEED's scientific advisory board (SAB): Prof. Rob van der Voo (University of Michigan, USA), Prof. Linda Elkins-Tanton (University of Arizona, USA), Prof. Michael Gurnis (Caltech University, USA), Prof. Sierd Cloetingh (Utrecht University, the Netherlands), and Prof. R.Dietmar Müller (University of Sydney, Australia). In 2014 we have invited three additional scientists of international caliber to join CEED's SAB: Prof. David Bercovici (Yale University, USA), A/Prof. Karin Sigloch (Oxford University, UK) and Prof. Mioara Mandea (CNES, France). This action was taken to diversify the SAB expertise (geodynamics-Prof. Bercovici, seismology-Prof. Sigloch and geophysics/satellite based spatial research- Mandea), to have more SAB members with European research expertise (Sigloch and Mandea), and to improve the gender balance in the SAB (now 3 out of 7 members are females). Before C. Gaina became CEED Director, Prof. R.D. Müller (Gaina's PhD adviser) withdrew from CEED SAB at the advice of its Chair, Prof. R. van der Voo.

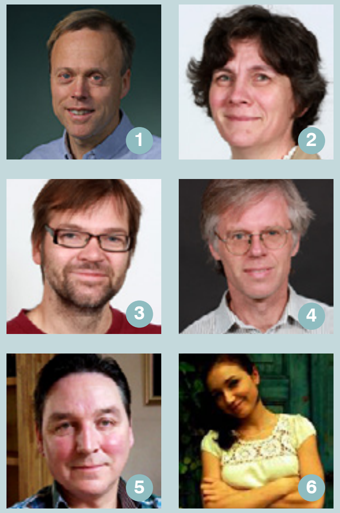
At the moment, CEED's SAB is chaired by Prof. Emeritus R. van der Voo (University of Michigan, USA) and its members are: Prof. D. Bercovici (Yale University, USA), Prof. Emeritus S. Cloetingh (Utrecht University, the Netherlands), Prof. L. Elkins-Tanton (University of Arizona, USA), Prof. M. Gurnis (Caltech University, USA), Prof. M. Mandea (CNES, France) and A/Prof. K. Sigloch (Oxford University, UK).

The SAB meets once a year; four meeting were organized at CEED, Oslo, in May 2013, 2014, 2015 and 2016. At these annual meetings the SAB receives updates on CEED's scientific activity from team leaders and other CEED members, and holds a meeting with CEED Directors for giving feedback and advices. More details about the outcome of these meetings are in the **"Self-evaluation report from the centre director"** document.

Research groups with research leaders (PIs), researchers and fellowships

Research Team Deep Earth:

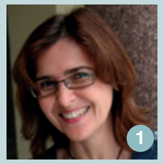
1 Reidar G. Trønnes (Professor 75%, Team Leader)
2 Valerie Maupin (Professor)
3 Chris E. Mohn (Researcher)
4 Bernhard Steinberger (Adjunct Researcher)
5 Wim Spakman (Adjunct Professor)
6 Marzena A. Baron (PhD student)



Management, Administrative and Technical staff

1 Carmen Gaina (Director)
2 Trond H. Torsvik (Assistant Director)
3 Trine-Lise K. Gørbitz (Administrative Leader)
4 Anita Sørlie (Administrative staff member)
5 Anniken R. Birkelund (Administrative Coordinator, DEEP Research School)
6 Petter Silkoset (Research Technician, National Geomagnetic Laboratory)
7 William Hagopian (Research Technician)

Note: x%, means x% of the time affiliated with CEED, according to the contract with NRC



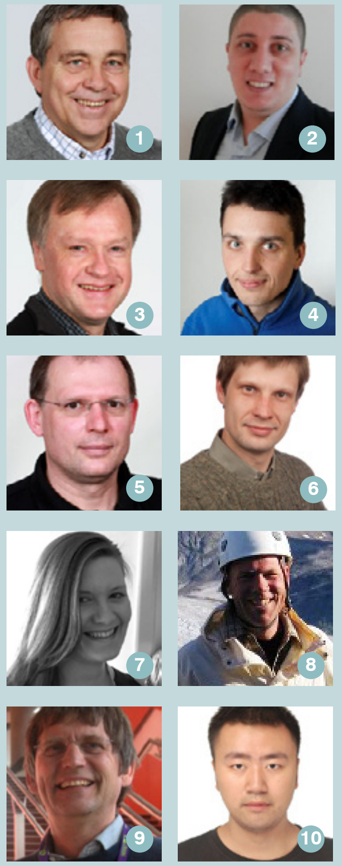
Research Team Dynamic Earth:
1 Trond. H. Torsvik
(Professor, Team Leader)

Working Group
Oceanic Basins and Climate Changes:

1 Carmen Gaina (Professor, Working Group Leader)
2 Judy Hannah (Researcher 50 %)
3 Holly Stein (Researcher 50 %)
4 Grace Shephard (Postdoc)
5 Valentina Magni (Postdoc)
6 Kerim Niscancioglu (Adjunct Professor)
7 Juan Carlos Afonso (Adjunct Professor)
8 Joost M. van den Broek (PhD student)
9 Eivind Straume (PhD student)
10 Svet Georgiev (Research Associate)

Working Group
Integrated Basin and Lithospheric Studies:

1 Jan Inge Faleide (Professor 30 %, Working Group Leader)
2 M. Mansour Abdelmalak (Researcher)
3 Asbjørn Breivik (Associate Professor)
4 Alexander Minakov (Postdoc)
5 Sergei Medvedev (Researcher)
6 Alexey Shulgin (Postdoc)
7 Leanne Cowie (Postdoc)
8 Ebbe H. Hartz (Adjunct Researcher)
9 Johannes Schweitzer (Adjunct Researcher)
10 Pingchuan Tan (PhD student)



Working Group
Margins and orogeny:

1 Torgeir B. Andersen (Professor 75%, Working Group Leader)
2 Fernando Corfu (Professor 20 %)
3 Roy Gabrielsen (Professor 30 %)
4 Susanne Buiter (Adjunct Researcher)
5 Johannes Jakob (Postdoc)
6 Hans Jørgen Kjøll (PhD student)

Research Team Earth Crisis:

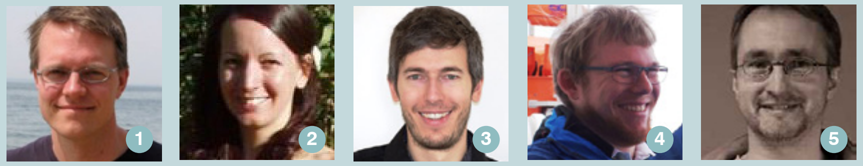
1 Henrik Svensen (Researcher, Team Leader)
2 Anne Hope Jahren (Wilson Professor)
3 Frode Stordal (Professor 20 %)
4 Adriano Mazzini (Researcher)
5 Wolfram Kürschner (Professor 30 %)
6 Dougal Jerram (Adjunct Researcher)
7 Else Ragnhild Neumann (Professor Emerita)
8 Sverre Planke (Adjunct Professor)
9 Alexander Polozov (Adjunct Researcher)
10 Morgan Jones (Researcher)
11 Marine Collignon (Postdoc)
12 Lars Eivind Augland (Postdoc)
13 Mohammad J. Fallahi (Postdoc)
14 Sara Callegaro (Postdoc)
15 Thea H. Heimdal (PhD student)
16 Alexandra Zaputlyaeva (PhD student)
17 Karyono (PhD student, Indonesia)
18 Alwi Husein (PhD student, Indonesia)

Research Team Earth and Beyond:

1 Stephanie Werner (Associate Professor, Team Leader)
2 Henning Dypvik (Professor 30 %)
3 Tobias Rolf (Postdoc)
4 Aswin Sekhar (Postdoc)
5 Jean-Christophe Viennet (Postdoc)
6 Benjamin Bultel (Postdoc)
7 Nils Prieur (PhD student)
8 Sruthi Uppalapati (PhD student)
9 Vera Fernandes (Research Associate)
10 Zhiyong Xiao (Research Associate)

Research Team Earth Modelling:

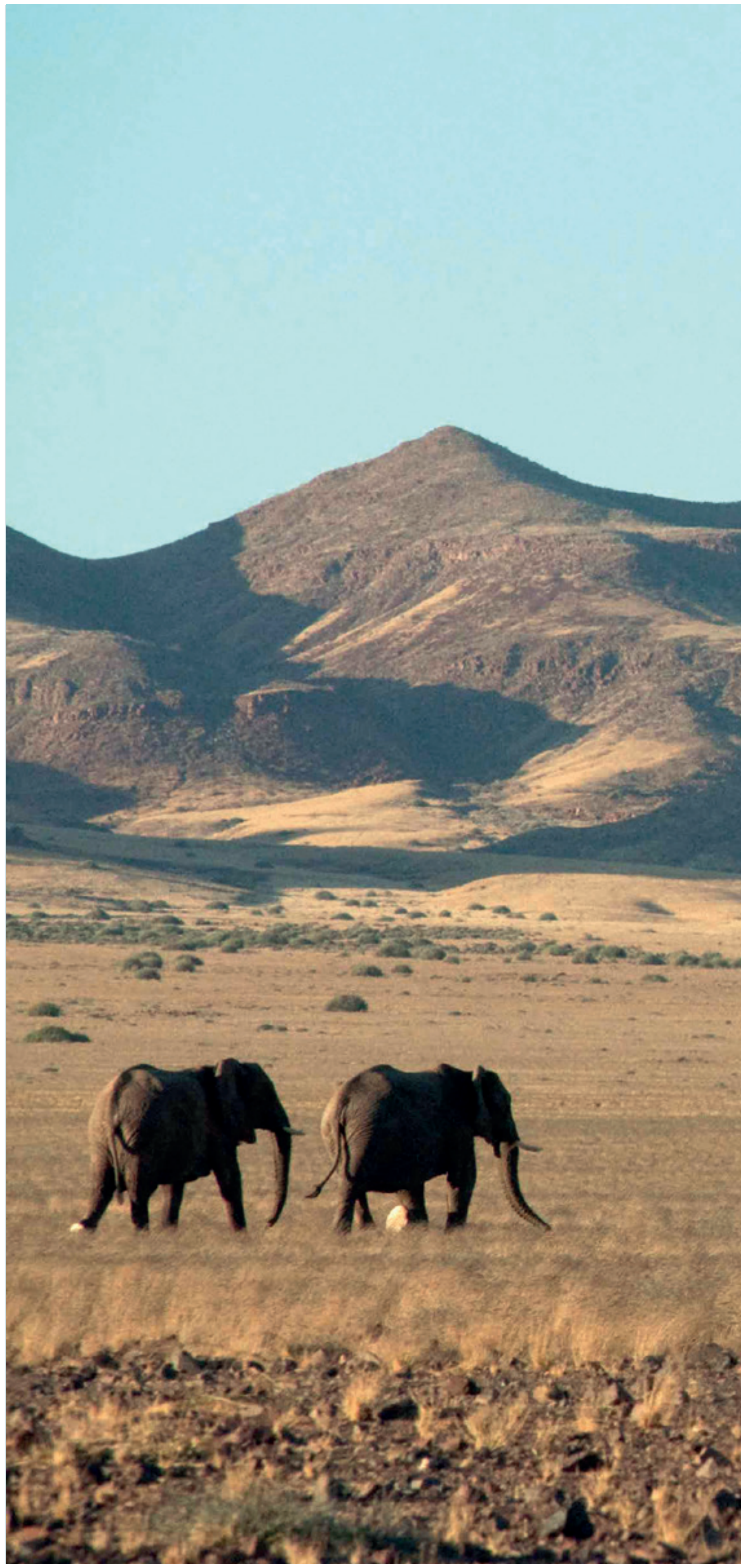
1 Clint Conrad (Professor, Team Leader)
2 Abigail Bull-Aller (Researcher)
3 Fabio Crameri (Postdoc)
4 Björn H. Heyn (PhD student)
5 Robin Watson (Research Associate)



Research Team Earth Laboratory

1 Pavel Doubrovine (Researcher, Team Leader)
2 Mathew Domeier (Researcher)
3 Evgeniy Kulakov (Postdoc)
4 Erik Halvorsen (Research Associate)

Short descriptions of CEED research groups



Earth Crises' mission is to explore and test the scientific breakthroughs and ideas developed by CEED scientists and others in the past decade about environmental effects of Large Igneous Provinces (LIPs), and to bridge the gap between the geological processes (mantle and lithosphere) and environmental perturbations. We will focus on developing and testing new hypotheses on how volcanic processes may have caused global stratigraphic boundary events.

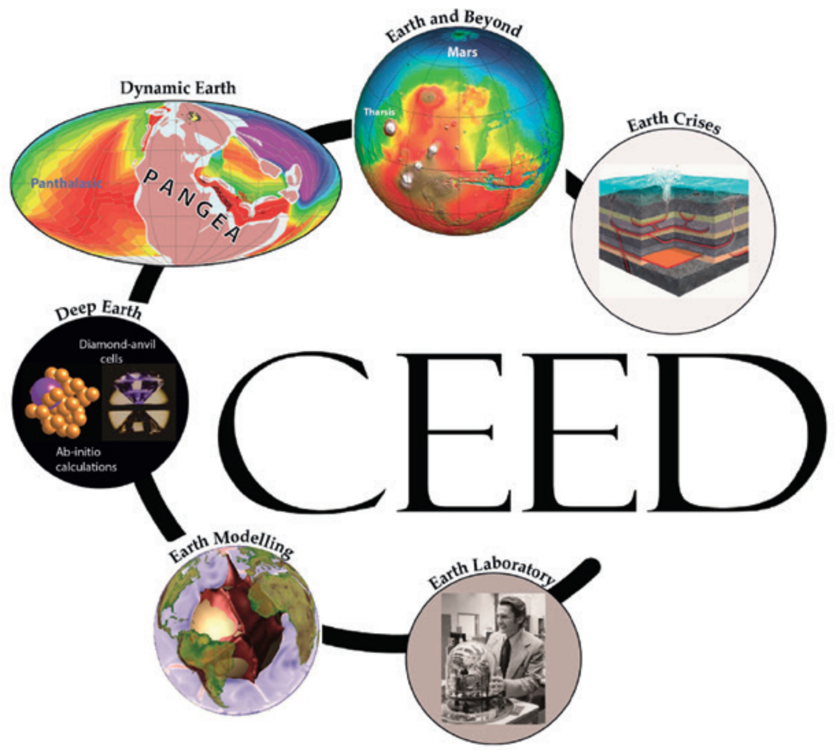
Earth and Beyond studies similarities and differences between Earth and other terrestrial planets, and notably why Earth is the only planet with plate tectonics. One of the tools we use to determine planetary surface ages is based on cratering statistics. Linking the surface evolution to interior conditions and processes (volcanism and tectonics) tells how and when the planet was still active.

Earth Modelling aims to decipher the relationship between the evolution of the mantle and historical plate tectonics. The interdisciplinary nature of CEED provides an ideal research environment for multi-system numerical models. Using inputs from a great diversity of disciplines, including geology, physics, mathematics, chemistry, palaeoclimatology, palaeontology, tectonics, palaeomagnetism, geodynamics, seismology, mineral physics, planetology and atmospheric sciences, CEED researchers are performing numerical models which enable analysis and interpretation of biological, geological, climate, geographical and dynamical data in time and space.

Deep Earth group studies mineralogy, material properties and dynamics of the lowermost mantle near the core-mantle boundary (CMB). The two antipodal large, low shear velocity provinces (LLSVPs) at CMB and their role in interacting with subducted oceanic slabs and as potential mantle plume generators are key research targets in this group. We also pursue the structure and evolution of mantle flow by convection modelling and geochemical fingerprinting of oceanic basalts. The phase relations and mineral physics of the D" layer minerals are key issues being investigated and melting experiments on mantle rocks that provide constraints on deep Hadean melting and crystallization and the origin and nature of LLSVPs.

The E**arth Laboratory** team is responsible for running and maintaining the Ivar Giæver Geomagnetic Laboratory, a Norwegian national research infrastructure for palaeomagnetism and rock magnetism, and is committed to providing state-of-the-art laboratory facilities and scientific expertise in the fields of palaeo- and rock magnetism to all researchers at CEED, our partner institutions, and nationally. This group focuses its research on generating high-quality paleomagnetic data and using these data for reconstructing Earth's palaeogeography.

Dynamic Earth is studying Earth's lithosphere and its interactions through time with the mantle, the oceans and the atmosphere through the Wilson cycle by combining numerous geological and geophysical data. Key topics studied in this team are: the evolution and dynamics of continental and oceanic lithosphere and links with upper and lower mantle and plume dynamics; connections between slab subduction, collision, glaciation and palaeotopography; and links between Wilson cycles, True Polar Wander and long-term climate trends.



Researcher training

– PhD in the centre including a list of PhD dissertations so far (+ gender), postdoc training, courses

CEED Researcher training 2013-2017

PhD researcher training

Currently, 13 (4 female) PhD students are employed at the Centre for Earth Evolution and Dynamics. The Faculty of Mathematics and Natural Sciences (MatNat) has an in-kind contribution to centers of excellence providing 3 KD (financed by the ministry of education) PhD positions at a given time. Three KD PhD candidates were recruited in 2013. One of these candidates defended his PhD thesis in November 2016, and continues to work at CEED as a RCN project postdoctoral researcher. Counting all PhD students affiliated with the centre (as of Dec. 2016), 5 PhD candidates (2 females) started only in 2016. Out of all PhD candidates who started at CEED from 2013, four left without finishing the course of their PhD studies, and are now employed in non-academic permanent positions (one of them has been hired as an engineer and technical assistant for the Earth Laboratory group).

List of PhD dissertations:
Johannes Jakob (male, defence date: Nov. 11, 2016) Title: Geodynamic Significance of Regional Mélange Units at Divergent and Convergent Plate Margins – Case Studies from the Scandinavian Caledonides and the North American Cordillera.

National Research School –DEEP (2016-2024) awarded to CEED and partners in 2015
A consortium of the four leading Norwegian universities headed by CEED members (Werner, Trønnes and Gaina) won the RCN grant to establish a national research school (NRS) active for a period of eight years (2016-2024) at CEED under the directorship of A/Prof. S. Werner. Norwegian research schools are meant to establish and coordinate courses on specific common academic themes for PhD students enrolled at Norwegian universities. The Norwegian Research School DEEP-Dynamics and Evolution of the Earth and Planets- focuses on four overarching themes: (1) Planetary physics and global tectonics, (2) Planetary interior: materials, structure and dynamics, (3) Solid Earth: composition and evolution, (4) Solid Earth - Fluid Earth interactions. According to these themes, new PhD courses were established at UiO, each worth 5 ECTS (credit) points. Norwegian doctoral training includes compulsory course work qualifying for 30 ECTS points, and normal, semester-long courses are usually 10 ECTS. Therefore, the availability of DEEP intensive (1 week long) courses on highly specialised topics gives PhD students more flexibility and greater efficiency in completing their study programs. Besides these intensive courses, DEEP organises topical workshops and soft-skills courses. They include special training in outreach activities, and presentation and writing skills. Open to the more experienced members of the school, DEEP provides training in supervision skills for young researcher (postdocs). To encourage student mobility, the school offers students travel stipends for shorter research visits and specialized courses at laboratories or facilities of the national and international partners of the school. PhD mobility mini-grants allow the access to knowledge, lab facilities and instruments that are not available in Oslo or in Norway, at large. DEEP collaborates with 11 international Universities and Institutes.

CEED as a partner in National Research School –CHESS (2016-2024) hosted by the University of Bergen
CEED is a national partner in the CHESS (Changing Climates in the Coupled Earth System) Research School hosted by the Geophysical Institute at the University of Bergen (http://www.uib.no/en/rs chess#). CHESS aims to train a new generation of researchers that have strong in-depth knowledge in their specific parts of the climate system, but at the same time are equipped with a broader knowledge to comprehend the overall picture in the coupled Earth System. At the moment, two CEED PhD students and their super–visors (including co-supervisors from Bergen University) are CHESS members and participate in CHESS activities.

CEED as partner in European Training Networks (ETNs)
CEED is a beneficiary in the SUBITOP ETN (Understanding subduction zone topography through modelling of coupled shallow and deep processes, 2016-2019) led by GFZ (Germany) - a framework for training and career development of 15 Early Stage Researchers (ESR) in Geodynamics, Geophysics, Geology and Geomorphology. SUBITOP ETN has a scientific focus on the dynamics of continental margins where tectonic plates are recycled through subduction. CEED is training 1 SUBITOP ESR towards a PhD degree.

Training of postdoctoral researchers

26 (8 female) postdoctoral researchers have been employed by CEED since 2013, of which 7 (3 female) started in 2016. There are two categories of postdoctoral researchers – one group is formed from postdocs hired for predefined projects, and the other includes postdocs who defined their own projects. From the latter group, 5 young researchers were hired by CEED in 2016 according to their excellence in research and their own project topics. All early career researchers are encouraged and supported to apply for RCN, ERC or other research grants that will give them more scientific independence and further their career paths. Since 2013, four young researchers who were working on predefined projects won their own grants: two RCN Young Researcher Talent grants (YFF), one VISTA postdoctoral grant, and one RCN postdoctoral mobility grant. CEED Founding director, T.H. Torsvik, has overseen the RCN and ERC application process and advised all applicants during the proposal writing. MatNat at UiO is also offering special support to all ERC and YFF applicants.

Based on Scopus search ("Earth AND Evolution AND Dynamics AND Oslo), there are 191 peer-reviewed papers published by researchers affiliated with CEED (as of Feb. 2017). Of these, 23 are led by postdoctoral researches, 2 by PhD students, and 2 by master students. In addition, postdoctoral researchers contributed to 13 papers, for which they are not first authors, and one PhD student contributed to one paper where the lead author is a postdoctoral researcher. The Centre actively supports the research of the young researchers, who need to build their own independent career for future grants and employment options.

At CEED we also encourage early career researchers to participate in the supervision of master and PhD students. A very good example is shown by the Master project of Ms. Eva Fritzell who was supervised by two early career researchers: Abigail Bull-Aller (Earth Modelling group) and Grace Shephard (Dynamic Earth group). The results from this thesis are published in Fritzell, E. H., A. L. Bull, and G. E. Shephard (2016), Closure of the Mongol-Okhotsk Ocean: Insights from seismic tomography and numerical modelling, Earth and Planetary Science Letters.

Research collaboration across research groups in the centre

– scientific results of collaborations in the centre and collaborative projects

EXAMPLE 1.

The **Earth Laboratory** team is responsible for running and maintaining the Ivar Giæver Geomagnetic Laboratory, a Norwegian national research infrastructure for palaeomagnetism and rock magnetism, and is committed to providing state-of-the-art laboratory facilities and scientific expertise in the fields of palaeo- and rock magnetism to all re–searchers at CEED, our partner institutions, and nationally. This group focuses its research on generating high-quality paleomagnetic data and using these data for reconstructing Earth's palaeogeography. In that regard, the group most actively collaborates with the **Dynamic Earth** group by providing data and models for paleogeographic reconstructions of continents and smaller tectonic blocks. Subsequently, global and regional, full plate-polygon models for the evolution of the Earth's lithosphere are constructed by scientists from both groups through a comprehensive integration of palaeogeographic and tectonic data, including palaeomagnetic, palaeobiologic, structural, stratigraphic, petrologic, geochemical and geochronological data (e.g., Domeier & Torsvik, 2014; Domeier, 2015).

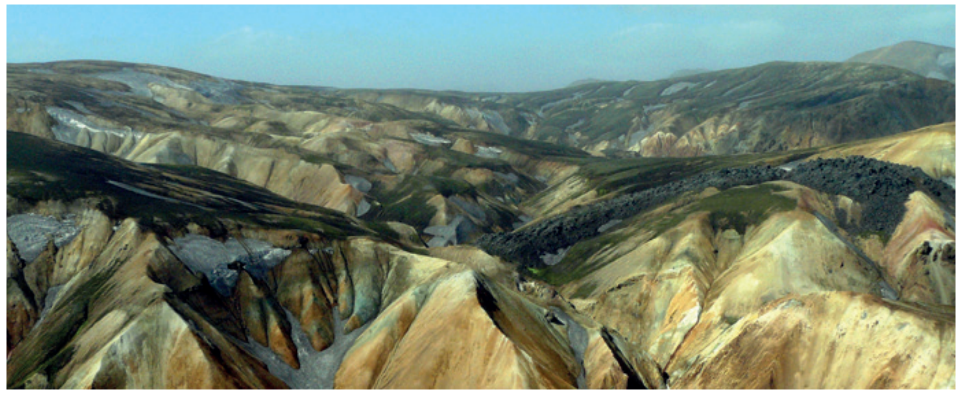
A particular emphasis is given to linking the paleogeography with absolute plate reconstructions in the mantle reference frame through the analysis of true polar wander (e.g., Doubrovine et al., 2012). The examples of collaboration between the Earth Laboratory and Dynamic Earth groups include the development of the first continuously-closing plate polygon model for the late Palaeozoic (Domeier & Torsvik, 2014), a plate tectonic model for the evolution of the Iapetus and Rheic oceans in the early Palaeozoic (Domeier, 2015), and a paleomagnetic study of Neoproterozoic sediments in northeast Svalbard to investigate a hypothesis regarding a true polar wander event in the Neoproterozic and to further refine the age of deposition of the sediments (PhD project in progress, Kjøll). The group is currently involved in a collaborative project aimed at building a complete plate tectonic model for the entire past 600 Myr of the Earth history; this is an YFF (Young Talents) RCN project led by M. Domeier. The integrated plate tectonic models can be further used for testing the links between the surface tectonics and deep mantle processes (e.g. Torsvik et al., 2014; Doubrovine et al., 2016; Domeier et al., 2016) and serve as input for numerical models of mantle convection (e.g., Bull et al., 2014) – thus linking the research activities of the Earth Laboratory team with those spearheaded by the Earth Modelling and Deep Earth groups.

Figure 1. DEEP's first course: Earth and Planetary Materials and Dynamics - April 2016.

EXAMPLE 2.

An important objective for CEED is to understand how the structure and dynamics of the mantle modulate the heat flow from the deep interior and thereby evolution of the Earth. Our current working hypothesis is that the degree-2 pattern of ascending flow above the Large Low Shear wave Velocity Provinces (LLSVPs) in the D" zone and the descending counterflow in the longitudinal high-velocity belt through the Arctic, Asia, Australia, Antarctica and the Americas have been operative throughout the Phanerozoic and possibly since the Hadean (e.g. Torsvik et al. 2014, PNAS; Torsvik et al. 2016, CJES). **The Deep Earth materials** group investigates the origin, composition and physical properties of candidate materials of the LLSVPs and Ultra-Low Velocity Zones (ULVZs), as well as the properties of the ambient mantle and recycled oceanic crust (ROC) (e.g. Baron et al. 2017, EPSL, in review; Mohn and Trønnes 2016, EPSL). Members of the **Earth Modelling, Dynamic Earth, Earth Laboratory and Deep Earth dynamics** groups study the lower mantle flow by a combination of convection modelling, analysis of seismic tomography data and Phanerozoic plate movement reconstructions (e.g. Conrad et al. 2013, Nature; Bull et al. 2014, EPSL; Torsvik et al. 2014, PNAS; Fritzell et al. 2016, EPSL; Shepard et al. 2016, GRL; Domeier et al. 2016, GRL). The development of Earth reference frames and models for true polar wander is also central in these studies.

The recently started PhD project of Björn Heyn, supervised by Clint Conrad and Abigail Bull (Earth modelling group) and Reidar Trønnes (Deep Earth group) will focus on the lateral flow in a low-viscosity D"-zone and the steady-state and pervasive flow ascending above the LLSVP interiors and the episodic and localised flow above the LLSVP margins. In these convection models we will try to incorporate the mineral physics properties of the commonly expected materials, i.e. LLSVPs with a stable and isolated lower layer of Fe-rich bridgmanite-dominated late-stage magma ocean cumulates (perhaps only about 100 km thick) with overlying unstable accumulations of ROC, that may partly become entrained in the rising flow. Modeling the formation and rise of large mantle plumes from the D" zone is also an important objective of these investigations.



Research collaboration across research groups in the centre

– scientific results of collaborations in the centre and collaborative projects

EXAMPLE 3.

The **Earth Crises** team is interested in episodes of Earth history when there were significant and rapid changes to the ocean-atmosphere system. The principal aim is to identify possible drivers of rapid climate change, including the emplacement of large igneous provinces and/or changes in plate tectonic regimes. In this framework, volcanic activity is of particular interest to the **Dynamic Earth** team, as regionally distributed volcanic ash layers can act as marker horizons in sedimentary sequences, allowing for correlations between basin-scale development and regional tectonics. To this end, Grace Shephard (postdoctoral researcher, VISTA fellow), Lars Augland (postdoctoral researcher), and Morgan Jones (YFF Young Research Talent from RCN) have joined forces to investigate a series of developments that preceded the opening of the northeast Atlantic Ocean.

The Central Basin in southern Svalbard formed as a strike-slip foreland basin during the Palaeogene, adjacent to the West Spitsbergen fold-and-thrust belt. The creation of this basin is inherently linked to the changes in the relative plate motions of North America, Greenland, and Eurasia, driven in part by the propagation of seafloor spreading in the Labrador and Norwegian-Greenland Seas. The Palaeocene and Eocene are of general interest due to numerous climatic and environmental changes that occurred, however, the exact timings of certain key events are poorly refined. An improved chronostratigraphy, via chemical fingerprinting and high precision U-Pb radioisotopic dating, of the formation and evolution of the Central Basin, can therefore be used to improve the regional geochronology and link far-field and basic-scale processes. Throughout the strata are prominent bentonite clay horizons of volcanic origin.

Geochemical analyses indicate that basal ash layers bear a close chemical affinity to another volcanic suite (Kap Washington Group) in north Greenland, whilst later ashes have been source from rift volcanism in the Nares Strait between Ellesmere Island and Greenland. Radiogenic isotope dating constrains the first deposition in the basin to ~61.76 Ma, providing a precise time that the foreland basin began developing in earnest. This also constrains the timing of a change in plate motions that instigated compression between Greenland and Svalbard, likely to be due to the acceleration of seafloor spreading in the Labrador Sea and/or the arrival of the North Atlantic Igneous Province plume head beneath eastern Greenland. In addition to on-going work, publications resulting from this collaboration were published in the *Journal of Volcanology and Geothermal Research* in 2016 (Jones et al, 2016); the geochronological work is being prepared for resubmission to *Nature: Scientific Reports* after revision (Jones et al., in review*).

*Jones, M.T., Augland, L.E., Eliassen, G.T., Burgess, S.D., Shephard, G.E., Jochmann, M., Friis, B., Jerram, D.A., Planke, S., Svensen, H.H. (2017). Constraining major shifts in North Atlantic plate motions during the Palaeocene by U-Pb dating of Svalbard tephra layers. *Nature: Scientific Reports*, in review.

EXAMPLE 4.

One of the recently started PhD projects involves the cooling of a planet by merging surface remote sensing data documenting tectonic and volcanic processes, with numerical modelling of the planets interior. Planet Earth is the test site for links between interior and surface processes, and establishing parameters for the numerical models. Initial parameters for other planets, e.g. Venus, are derived in analogy from Earth. The analogy between Earth and other planets helps to build stronger links between the **Earth Modelling** and the **Earth and Beyond groups.**

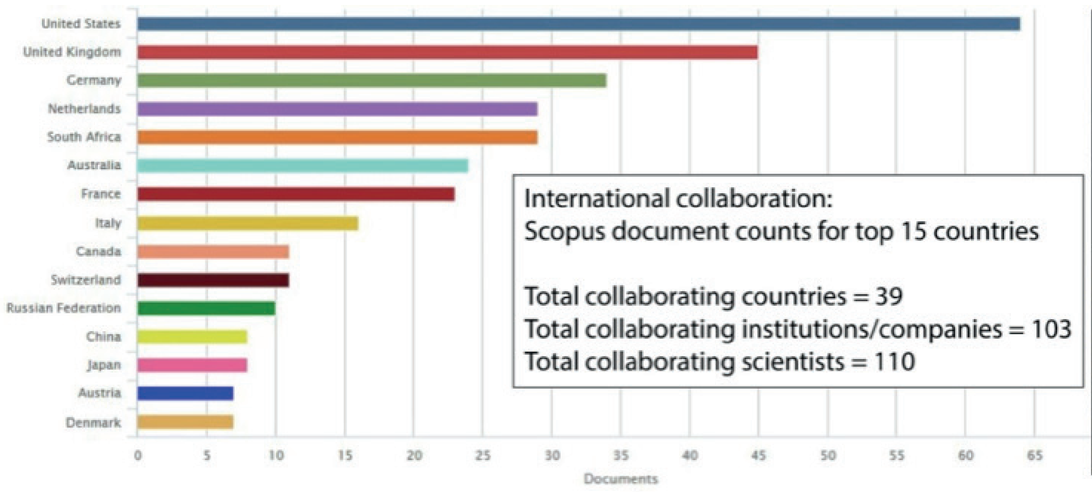
International collaboration

– scientific results of collaboration, co-authorship

CEED has a truly international collaboration profile which has resulted in authored or co-authored papers with ~110 scientists from 39 different countries (103 institutions/companies). US, UK and German scientists top the international publication document list – but in addition to joint publications – international collaboration have included joint field-operations in Indonesia, Svalbard, Denmark, North America, Canada, Russia, South Africa, Australia, Morocco, Mauritius, and cruises in the Indian Ocean and the Barents Sea (seismic and potential field data). Visiting exchanges and workshops (e.g. *the 13th International Workshop on Modelling of Mantle and Lithosphere Dynamics* with 96 participants) for both senior scientists and students have been extensive: Collaborators have used CEED laboratory facilities (Palaeomagnetic & U/Pb laboratories) whilst CEED students have been granted access to experimental facilities in the UK (Bristol), Germany (Bayreuth) and France (Strasbourg, Paris).

Practically all CEED scientists and PhD students are, to variable degrees, exposed to international collaboration, either funded directly by CEED or by other external funds. The project "Beyond Plate Tectonics" funded by an ERC Advanced Grant (Torsvik) was completed in 2016, and together with international partners (US, UK, Germany, the Netherlands, South Africa and Australia) this venture resulted in a first-order understanding of how plate tectonics and mantle plumes interact. Another international project LUSI LAB (ERC Starting Grant, Mazzini) focuses on understanding the plumbing system and the origin of the spectacular LUSI mud eruption in North-East Java.

In 2014 CEED won an EU H2020-COMPET grant Planetary Terrestrial Analogues Library (PTAL) a consortium project for 5 years coordinated by CEED (Werner). International consortium members include the Universities of Paris-Sud (France) and Valladolid (Spain). PTAL aims to build and exploit a spectral library with commercial and dedicated space instruments for the characterisation of the mineralogical and geological evolution of terrestrial planets and small Solar System bodies. Another example of international activity is SUBITOP **(Understanding subduction zone topography through modelling of coupled shallow and deep processes),** which is a European Training Network project. The network provides a framework for training and career development of young researchers from ten different European institutions.




The LUSI (CEED) drone operating in Indonesia


CEED drilling in Svalbard

SUBITOP is coordinated by Deutsches GeoforschungsZentrum (GFZ, Germany), and the principal investigator at CEED is Carmen Gaina. Extensive and targeted collaboration with other universities/ research institutions and international centres of excellence include Earth-Life Science Institute (ELSI, Tokyo Institute of Technology, Japan), Centre for Earth System Petrology (Aarhus University, Denmark), University of Utrecht (Netherlands), GFZ (Germany), and the Universities of Witwatersrand (South Africa), Bristol (UK), California, Sentra Barbara (US) and Alberta (Canada).

Outreach and popular science is prioritized at CEED as the third pillar of academia – in addition to research and teaching. Our outreach includes interactions with national and international journalists and media following the publication of high impact papers, lectures, being expert commentators in radio and TV on topics of societal interest, and producing a steady flow of our own writing in newspapers and books.

We discuss science with children on science fairs, publish popular science books, talk about natural phenomena – like earthquakes - on the most popular teenage radio channel in Norway, publish papers that make it to top two on worldwide news channels (BBC and CNN), and talk about shale fracking with members of the National Academy of Science and Letters in Oslo. We have made hundreds of contributions over the last few years, sharing our ideas and knowledge and interact with society. We communicate on Facebook, on Twitter, on Wikipedia, we have our own blog – and contribute regularly as columnists to Morgenbladet (Norway) and Huffington Post.

To give you a flavor of what we do at CEED, have a look at the following selected cases.

Radio:

1. Svensen, H.H. (2015). Menneskets tidsalder. Norgesglasset NRK P1, 27 May (interview).
2. Svensen, H.H. (2014) NRK P2 Ekko. De store masseutryddelsene. Del 1: Ordovicium. 2014-10-15. (interview)
3. Kjøll, H.J. (2016) Hallo P3 with Hans Jørgen Kjøll. Interview about earthquakes.

TV:

1. Torsvik, T. (2016) Minds of the Universe, http://www.themindoftheuniverse.nl/ (feature/series)
2. Mazzini, A., (2015) The Lusi volcano. Rai News Interview, TG Leonardo, 6 April. (interview)
3. Svensen, H.H. (2016) Fem tegn på at vi har skapt en ny tidsalder. VGTV (interview about the Anthropocene).
4. Andersen, T.B. (2016) Amatrice Earthquake in Italy 24. August 2016. Comments and explanations on National TV2 News channel.

Expert commentators in national and international science media

1. Sekhar A., 'Rare Cosmic Balancing Act makes Perseid meteor showers brighter' featured in New Scientist Magazine 26 May 2016 issue (https://www.newscientist.com/article/2090465-rare-cosmic-balancing-act-makes-perseid-meteor-showers-brighter/)
2. Svensen, H,H. How long will life survive on planet Earth? BBC, 23.03.2015 (interview).

Coverage of our research (interviews)

1. Titan Magazine: Drømmer om å avsløre hvordan jorda henger sammen. Interview with Trond Torsvik, 20th April 2016.
2. Geoforskning.no: Gåten er fortsatt ikke løst. Based on interview with Svensen and Planke.
3. Aftenposten Junior: Trønnes, Reidar G. 18.-24. Aug. 2015: 10 spørsmål og svar om vulkaner.

Books

1. Kristiansen, J.R; Evans, A.K.D.; Svensen, H; Samset, B.H; Byhring, H.S. (red) Stjerneklart – siste nytt fra verdensrommet. Spartacus 2015 (ISBN 9788243009738) 193 s. (popular science book)
2. Svensen, H.H. (2014) KIHEUb CBITY bANEbKO. Ukraine: Calvaria publishing house 2014. (Ukraine edition of a popular science book on natural disasters)
3. Jerram, D. (2015) Victor the Volcano. Rudling House, UK.

Lectures about outreach

1. Svensen, H.H. (2015) Åtte teser for forskningsformidling. Talk at an outreach seminar at Høgskolen i Østfold, Fredrikstad. 08.10.2015.
2. Svensen, H.H. (2015) Communicating science. PhD/Postdoc Day at CEES/UiO, the Norwegian Academy of Science and Letters.

Popular science writing

1. Torsvik, T.H, Trønnes, R.G. (2015) Deeply buried continental crust under Iceland. Forskning.no (popular science article based on own paper).
2. Planke, S. (2016) Blandt glødende lava og giftige gasser. GEO magazine (story based on a CEED expedition to East Russia.
3. Svensen, H.H. (2016) Vulkanutbruddene som endret alt. May 2016, Aftenposten (popular science article based on own scientific paper).
4. Svensen, H.H. (2014) Frihet i antropocen. I: Ja, vi elsker frihet. Dreyer Forlag A/S. (essay in the University of Oslo 200 year anniversary anthology).
5. Kjøll, H.J. (2016) Dette er de fem vakreste bergartene. Titan Magazine (online magazine published by UiO).
6. Svensen, H.H. Grønne grunnstoffer. *Morgenbladet* (science writing column in national newspaper).

Public talks

1. Andersen, T.B. (2016) Risk and management of earthquakes, event at the Italian Embassy in Oslo, 13 December.
2. Jahren, A. Hope (2016) 30 Things That Everyone Should Know About Global Change. The Wilson Lecture for 2016 at UiO.
3. Svensen, H.H. (2015) Anthropocene, or the age of man. Ultimafestivalen (talk at a contemporary music festival in Oslo).

Our Facebook and Twitter profiles

Facebook (total of about 300 followers): @centreforearthevolutionanddynamics and @researchDEEP

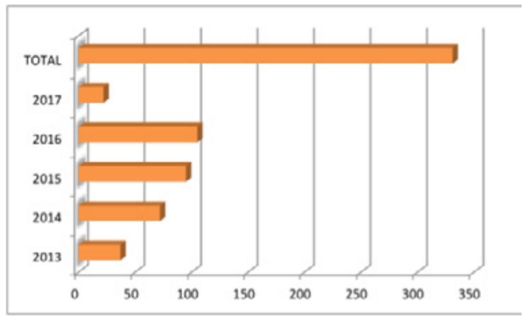
Twitter (total of about 700 followers): @CEEDOslo and @ResearchDEEP

Figure 2. Elementary school children learning about Earth and planets at CEED booth, Science Fair, September 2016, Oslo

Publication list

	Peer Reviewed-Journals	Peer Reviewed-Book Chapters	Books	Conference Abstracts
2013	37	2		160
2014	72	4		148
2015	95	10		196
2016	105	1	1	160
2017 * to March 1st	22			30
TOTAL	**331**	**17**	**1**	**694**

*until 1 March 2017



The following list includes SCOPUS publications with CEED affiliation (note –not all publications by CEED members have CEED as affiliation, especially personnel with part-time association).

Selected publications (CEED authors underlined)

(indicates author list in alphabetical order; # - 1st author CEED Postdoctoral Fellow; ## - 1st author CEED PhD or Master student)*

I. Peer-reviewed – Journals (120 out of 331)

1. #Abdelmalak, M. M., S. Planke, J. I. Faleide, D. A. Jerram, D. Zastrozhnov, S. Eide, and R. Myklebust (2016b), The development of volcanic sequences at rifted margins: New insights from the structure and morphology of the Vøring Escarpment, mid-Norwegian Margin, *Journal of Geophysical Research: Solid Earth, 121*(7), 5212-5236.
2. #Abdelmalak, M. M., T. B. Andersen, S. Planke, J. I. Faleide, F. Corfu, C. Tegner, G. E. Shephard, D. Zastrozhnov, and R. Myklebust (2015), The ocean-continent transition in the mid-norwegian margin: Insight from seismic data and an onshore caledonian field analogue, *Geology*, *43*(11), 1011-1014.
3. #Abdelmalak, M. M., R. Meyer, S. Planke, c, J.I. Faleide, L. Gernigon, J. Frieling, A. Sluijs, G.-J. Reichart, D. Zastrozhnov, S. Theissen-Krah, A. Said, R. Myklebust (2016c), Pre-breakup magmatism on the Vøring Margin: Insight from new sub-basalt imaging and results from Ocean Drilling Program Hole 642E, *Tectonophysics, 675*, 258-274.
4. Andrault, D., R. G. Trønnes, Z. Konôpková, W. Morgenroth, H. P. Liermann, G. Morard, and M. Mezouar (2014), Phase diagram and P-V-T equation of state of Al-bearing seifertite at lowermost mantle conditions, *American Mineralogist*, *99*(10), 2035-2042.

5. Ashwal, L. D., M. Wiedenbeck, and T. H. Torsvik (2017), Archaean zircons in Miocene oceanic hotspot rocks establish ancient continental crust beneath Mauritius, ***Nature Communications***, *8*.
6. Brasser, R., S. Matsumura, S. Ida, S. J. Mojzsis, and S. C. Werner (2016a), ANALYSIS Of TERRESTRIAL PLANET FORMATION By The GRAND TACK MODEL: SYSTEM ARCHITECTURE And TACK LOCATION, *Astrophysical Journal, 821*(2).
7. Brasser, R., S. J. Mojzsis, S. C. Werner, S. Matsumura, and S. Ida (2016b), Late veneer and late accretion to the terrestrial planets, *Earth and Planetary Science Letters, 455*, 85-93.
8. Buiter, S. J. H., and T. H. Torsvik (2014), A review of Wilson Cycle plate margins: A role for mantle plumes in continental break-up along sutures?, *Gondwana Research, 26*(2), 627-653.
9. Buiter, S. J. H., F. Funiciello, and J. Van Hunen (2013), Introduction to the special issue on "subduction zones", *Solid Earth, 4*(1), 129-133.
10. Buiter, S. J. H., et al. (2016), Benchmarking numerical models of brittle thrust wedges, Journal of *Structural Geology, 92*, 140-177.
11. #Bull, A. L., M. Domeier, and T. H. Torsvik (2014), The effect of plate motion history on the longevity of deep mantle heterogeneities, *Earth and Planetary Science Letters, 401*, 172-182.
12. Coakley, B., K. Brumley, N. Lebedeva-Ivanova, and D. Mosher (2016), Exploring the geology of the central Arctic Ocean; understanding the basin features in place and time, *Journal of the Geological Society*, *173*(6), 967-987.
13. Conrad, C. P., B. Steinberger, and T. H. Torsvik (2013b), Stability of active mantle upwelling revealed by net characteristics of plate tectonics, ***Nature***, *498*(7455), 479-482.
14. Corfu, F., and T. B. Andersen (2016), Proterozoic magmatism in the southern Scandinavian Caledonides, with special reference to the occurrences in the Eikefjord Nappe, *GFF, 138*(1), 102-114.
15. Corfu, F., T. B. Andersen, and D. Gasser (2014a), The Scandinavian Caledonides: Main features, conceptual advances and critical questions, in *Geological Society Special Publication*, edited, pp. 9-43.
16. Deseta, N., T. B. Andersen, and L. D. Ashwal (2014a), A weakening mechanism for intermediate-depth seismicity? Detailed petrographic and microtextural observations from blueschist facies pseudotachylytes, Cape Corse, Corsica, *Tectonophysics, 610*, 138-149.
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18. #Domeier, M. (2016), A plate tectonic scenario for the Iapetus and Rheic oceans, *Gondwana Research, 36*, 275-295.
19. #Domeier, M., and T. H. Torsvik (2014), Plate tectonics in the late Paleozoic, *Geoscience Frontiers, 5*(3), 303-350.
20. #Domeier, M., P. V. Doubrovine, T. H. Torsvik, W. Spakman, and A. L. Bull (2016), Global correlation of lower mantle structure and past subduction, *Geophysical Research Letters, 43*(10), 4945-4953.
21. Doubrovine, P. V., B. Steinberger, and T. H. Torsvik (2016), A failure to reject: Testing the correlation between large igneous provinces and deep mantle structures with EDF statistics, *Geochemistry, Geophysics, Geosystems, 17*(3), 1130-1163.
22. *Ehlmann, B. L., et al. (including S. Werner) (2016), The sustainability of habitability on terrestrial planets: Insights, questions, and needed measurements from Mars for understanding the evolution of Earth-like worlds, *Journal of Geophysical Research E: Planets, 121*(10), 1927-1961.

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27. ##Fritzell, E. H., A. L. Bull, and G. E. Shephard (2016), Closure of the Mongol-Okhotsk Ocean: Insights from seismic tomography and numerical modelling, *Earth and Planetary Science Letters*, *445*, 1-12.
28. Gaina, C., D. J. J. Van Hinsbergen, and W. Spakman (2015), Tectonic interactions between India and Arabia since the Jurassic reconstructed from marine geophysics, ophiolite geology, and seismic tomography, *Tectonics*, *34*(5), 875-906.
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31. Gassmöller, R., J. Dannberg, E. Bredow, B. Steinberger, and T. H. Torsvik (2016), Major influence of plume-ridge interaction, lithosphere thickness variations, and global mantle flow on hotspot volcanism - The example of Tristan, *Geochemistry, Geophysics, Geosystems*, *17*(4), 1454-1479.
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II. Peer-reviewed –Book chapters (12 out of 17)

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3. Jones, M. T. (2015), The environmental and climatic impacts of volcanic ash deposition, In Anja Schmidt; Kirsten Fristad & Linda T. Elkins-Tanton (ed.), *Volcanism and global environmental change.* Cambridge University Press. ISBN 9781107058378. pp. 260-274.
4. Stein, H; Hannah, J. (2015). Rhenium-Osmium geochronology – sulfides, shales, oils, and mantle, in Rink, J. and Thompson, J. (eds), Earth Sciences Series, *Encyclopedia of Scientific Dating Methods*, Springer.
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III. Books

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As per 28.02.2017, CEED has 70 persons employed full-time and part-time (as “Adjunct” professors or Researchers), and 7 affiliated/guest researchers (including two Emeritus). A number of professors employed by the Department of Geosciences partially dedicate their research time to CEED (percentage as agreed with the host institute shown below).

Professors 12

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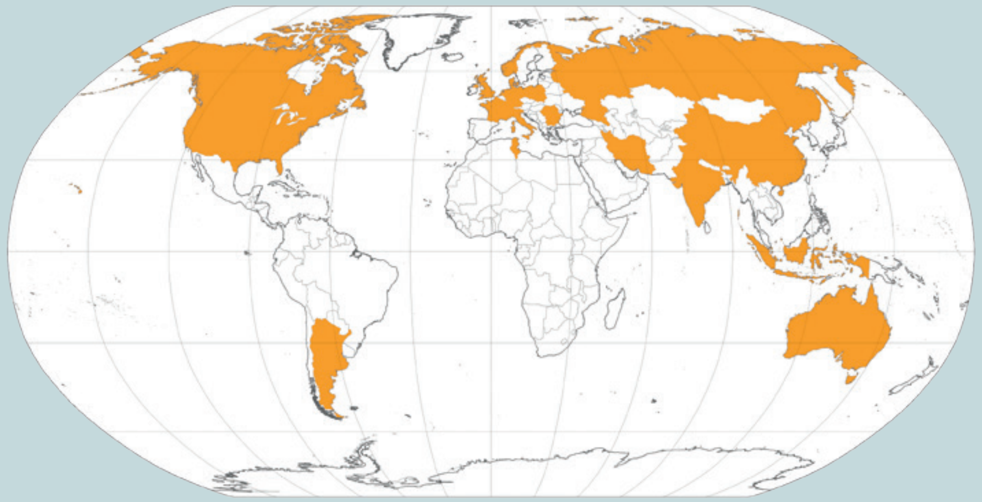
Conrad, Clinton P.
Corfu, Fernando 20%
Dypvik, Henning 30%
Faleide, Jan Inge
Gabrielsen, Roy H. 30%
Gaina, Carmen
Jahren, A. Hope Wilson Professor
Maupin, Valerie
Stordal, Frode 20%
Torsvik, Trond H.
Trønnes, Reidar G.

Researchers 9

Bull, Abigail Aller
Domeier, Mathew
Dubrovine, Pavel
Hannah, Judith (50% at Colorado State University, USA)
Mazzini, Adriano
Medvedev, Sergei
Mohn Chris E.
Stein, Holly (50% at Colorado State University, USA)
Svensen, Henrik

Associate Professors 2

Breivik, Asbjørn
Werner, Stephanie C.



Full list of personnel at the centre

Adjunct Researchers (20% position) 7

Buiter, Susanne (NGU)
Jerram, Dougal (DougalEarth)
Hartz, Ebbe (Aker)
Polozov, Alexander (IGEM RAS, Moscow)
Schweitzer, Johannes (NORSAR)
Steinberger, Bernhard (GFZ)
Watson, Robin (NGU)

Affiliated Researchers 7

Halvorsen, Erik (University of Bergen)
Fernandes, Vera (Museum für Naturkunde, Germany)
Georgiev, Svet (Colorado State University, USA)
Larsen, Bjørn T. (Emeritus)
Neumann, Else Ragnhild (Professor Emerita)
Watson, Robin (Geological Survey of Norway)
Xiao, Zhiyong (Beary) (University of Wuhan, China)

PhD students 13

Baron, Marzena Anna
Heimdal, Thea Hatlen
Heyn, Björn Holger
Husein, Alwi
Karyono
Kjøll, Hans Jørgen
Prieur, Nils Charles
Sætre, Christian
Straume, Eivind O.
Tan, Pingchuana UiO
Uppalapati, Sruthi
van den Broek, Joost M.
Zaputlyaeva, Alexandra

Adjunct Professors (20% position) 4

Afonso, Juan Carlos (Macquarie University, Australia)
Niscancioglu, Kerim Hestnes
(University of Bergen, Norway)
Planke, Sverre (VBPR, Norway)
Spakman, Wim (Utrecht University, the Netherlands)

Postdoctoral Fellows 19

Abdelmalak, M. Mansour
Augland, Lars Eivind
Bultel, Benjamin
Callegaro, Sara
Collignon, Marine
Cowie, Leanne
Crameri, Fabio
Fallahi, Mohammad J.
Jakob, Johannes
Jones, Morgan
Kulakov, Evgeniy
Magni, Valentia
Minakov, Alexander
Rolf, Tobias
Sekhar, Aswin
Shephard, Grace
Shulgin, Alexey A.
Viennet, Jean-Christophe

Technical-administrative staff members 4

Birkelund, Anniken R. The DEEP National Research School Administrator
Gørbitz, Trine-Lise, Administrative leader
Hagopian, William, Research technician
Silkoset, Petter Research technician

Fig. 1: Microcontinents ('lost continents') in the Indian Ocean. Dark blue shaded units were all part of the Mauritia microcontinent before 85 Ma (Torsvik et al. 2013; Ashwal et al. 2017). Inset figure – Microcontinents in the NE Atlantic such as Jan Mayen (brown shaded units) and its extension below Iceland (black unit) as we argue in Torsvik et al. (2015).

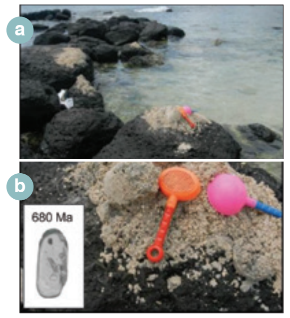
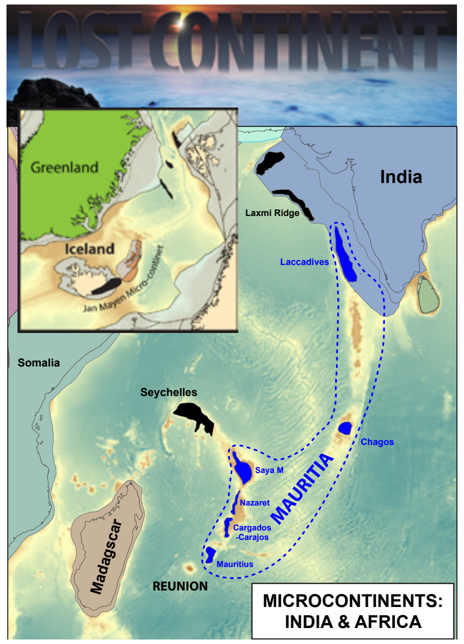


Fig 2: Beach sand was sampled next to deeply eroded basalt columns (panel a) and the sand was filtered to <2mm (panel b). The samples were then sealed until further processing at the University of Oslo. The sand concentrates were passed through 250 μm disposable sieves and the finer grained fraction further enriched with a Frantz magnetic separator and heavy liquid (methylene iodide), before the final hand-picking of zircons in alcohol under a binocular microscope. About twenty zircon grains were found and one of the zircons was dated to 680 million years (*inset picture in panel b*).

I. LOST CONTINENTS

The following three papers – ***searching for lost continents*** (Fig. 1) – are examples of exciting and curiosity-driven science which is a scientific spinoff of CEED's vision to link deep mantle processes and surface volcanism (e.g. hotspots). CEED spearheaded and funded these studies and the results were published in high-profile journals and attracted unparalleled media attention. Scientists from several CEED teams were involved and international collaboration (including field-work) included experts in petrology and geochemistry, U-Pb geochronology and geophysics from South Africa, Germany, Australia and the UK.



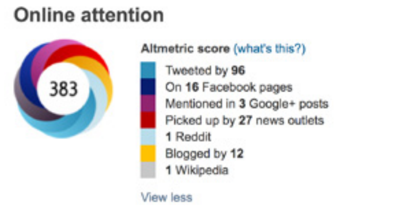
Paper 1

Torsvik, T.H., Amundsen, H., Hartz, E.H., Corfu, F., Kusznir, N., Gaina, C., Doubrovine, P., Steinberger, B., Ashwal, L.D., Jamtveit, B. **2013**. A Precambrian microcontinent in the Indian Ocean. ***Nature Geoscience***, 6, 223-227.

Microcontinents (small fragments of continental crust, stranded within oceanic realm) are a natural consequence of plate–mantle plume interactions. A classical example is the Seychelles in the Indian Ocean (Fig. 1). Evidence from surface exposures and seismic studies support the existence of a partly emergent 4–4.5 x 10^4 km² fragment of continental crust with a thickness of ~33 km. Less clear examples of microcontinents in the Indian Ocean include the Laxmi Ridge (Fig. 1), which has been interpreted as a sliver of thinned continental crust, or composed entirely of underplated oceanic crust. Geophysical data, in isolation, yield equivocal interpretations of oceanic crustal structures and compositions, but if used in conjunction with geochemical and/or isotopic data or with recovered mineral grains that require the presence of deep continental rocks, the results are much more accurate.

Our search for new microcontinents began with grains of sand collected from beaches on Mauritius. Mauritius forms part of the Southern Mascarene Plateau, thought to be a volcanic chain formed above the Réunion mantle plume. The island is almost entirely covered by young basalts (less than 9 million years old). Sampling beach sand eliminates the need for rock crushing and thus the chance for contaminating the sample with zircons from previously processed samples. Some twenty zircon grains were recovered from the beach sand and we used U–Pb dating (TIMS, thermal ionization mass spectrometry) to analyse the ages of zircon xenocrysts. Surprisingly, we found that the zircons were either Palaeoproterozoic (more than 1,971 million years old) or Neoproterozoic (between 660 and 840 million years old) and we proposed that the zircons were assimilated from ancient fragments of continental lithosphere beneath Mauritius, and were brought to the surface by younger plume-related lavas.

We further used gravity data inversion to map crustal thickness and found that Mauritius forms part of a contiguous block of anomalously thick crust that extends in an arc northwards to the Seychelles. Using plate tectonic reconstructions, we demonstrated that Mauritius and the adjacent Mascarene Plateau may overlie a Precambrian microcontinent that we named "Mauritia". On the basis of reinterpretation of marine geophysical data, we proposed that "Mauritia" was separated from Madagascar and fragmented into a ribbon-like configuration by a series of mid-ocean ridge jumps during the opening of the Mascarene ocean basin between 83.5 and 61 million years ago. Plume-related magmatic deposits have since covered "Mauritia" and potentially other continental fragments.



"Mauritia" – the lost or sunken continent – attracted massive international interest in the popular press: A Nature News article covering our story was among the 10 top most read articles in Nature 2013, and a BBC online article was read by 1.6 million readers on February 25th and only beaten that day by a report on the Oscar Winners 2013! But there would be much more on-line attention for "Mauritia" to come (see below).

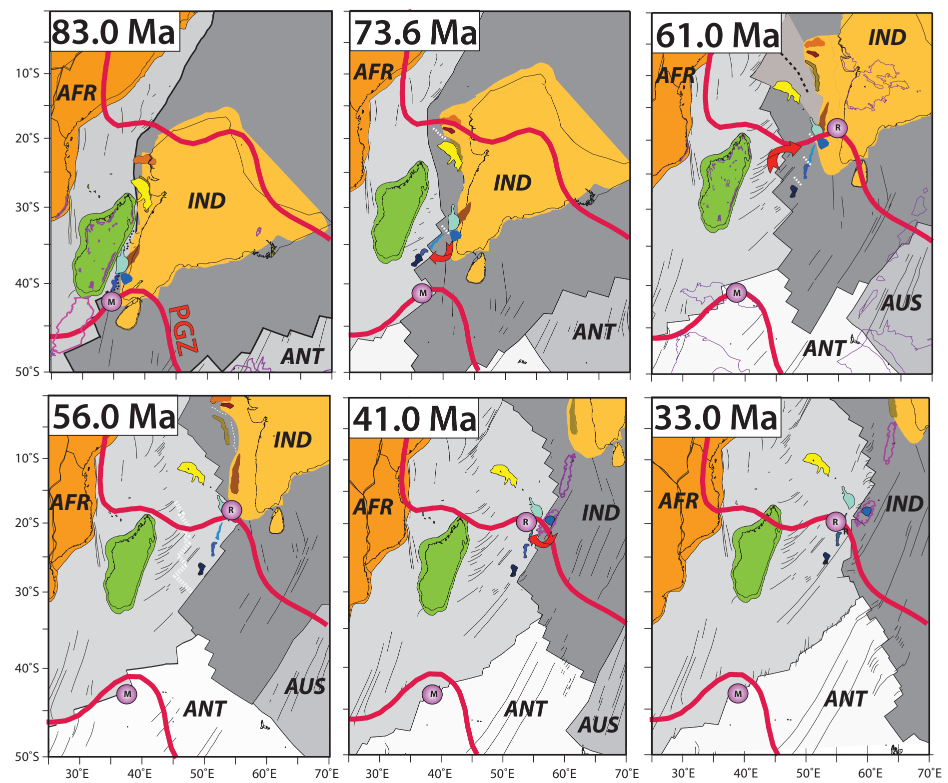


Fig. 3 Plate tectonic reconstructions from the Late Cretaceous to Miocene in an absolute reference frame. The predicted positions of Marion (M) and Reunion (R) hotspots (corrected for plume advection) are shown in magenta, and the thick red lines are the plume generation zones (PGZs) at the core-mantle boundary. Extinct spreading ridges between various microcontinents are shown as dashed white lines. We show that ridge jumps propagated SW while the Marion plume was in the proximity of the active plate boundary. Red arrows indicate direction of plate boundary relocation towards the closest hotspot. Oceanic floor fabric and direction of spreading between major tectonic plates are depicted by interpreted fracture zones. Outlines of major volcanic plateaus and provinces are shown in magenta. The plates are shown in different shades of grey and white: AFR, Africa; IND, India, AUS, Australia; ANT, Antarctica.

Paper 2

Ashwal, L.D., Wiedenbeck, M., Torsvik, T.H. 2017. Archaean zircons in Miocene oceanic hotspot rocks establish ancient continental crust beneath Mauritius. ***Nature Communications***. DOI: 10.1038/ncomms14086.

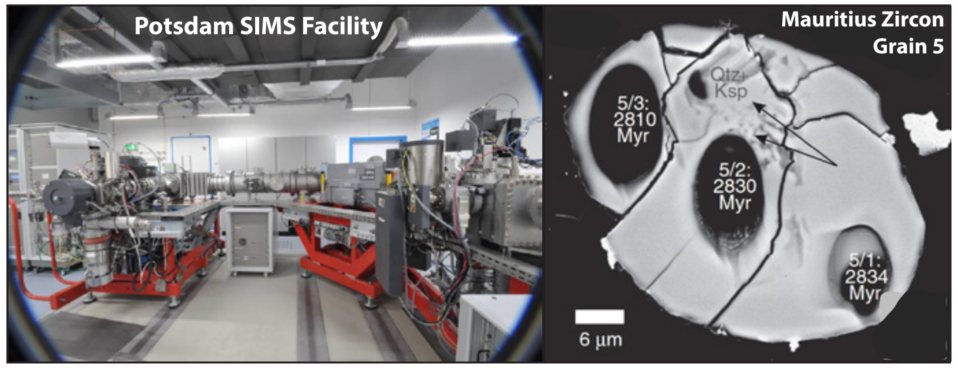


Fig. 4: The zircons in this study were analyzed in the SIMS-laboratory **(ion mass spectrometry)** of the GFZ German Research Centre for Geosciences (Potsdam). The right image shows the U-Pb spot ages of one zircon grain.

Mauritius is dominated by basaltic volcanism but minor volumes of trachytic rocks occur as intrusive masses or plugs less than 300 meters across and are associated with the Older Series (9.0–4.7 Ma) basalts. Mauritian trachytes are variably altered from probable primary phonolitic rocks, forming a prominent Daly Gap when plotted with coeval basalts. This suggests formation either by extreme fractional crystallization from the basalts or by direct partial melting of metasomatized mantle. Isotopic compositions of the trachytes show relatively constant ε_{Nd} of +4.03±0.15, with highly variable ISr of 0.70408–0.71034, which we recently interpreted as reflecting small amounts (0.4–3.5%) of contamination by Precambrian continental crust (Ashwal, L.D. et al. 2016. J. Petrol. 57, 1645–1676). It is from such a Mauritian trachyte that a population of zircons was extracted and analyzed for this paper.

Thirteen zircon grains were recovered in this study, from which we reported 68 individual point analyses acquired using the Cameca 1280-HR SIMS (secondary ion mass spectrometer) instrument at GFZ Potsdam. Three zircon grains show uniquely mid- to late-Archaean U–Pb systematics, with no evidence for Phanerozoic components; we conducted 20 individual U–Th–Pb spot analyses on these grains, where the concordant or near-concordant ages range from 3,030 ± 5 Ma to 2,552 ± 11 Ma (Fig. 5, note that the vertical axis should be $^{206}Pb/^{238}U$). We interpreted these data as indicating the crystallization ages of a complex Archaean xenocrystic component. As the three grains are distinct in terms of their crystallization ages as well as their Th/U systematics, we concluded

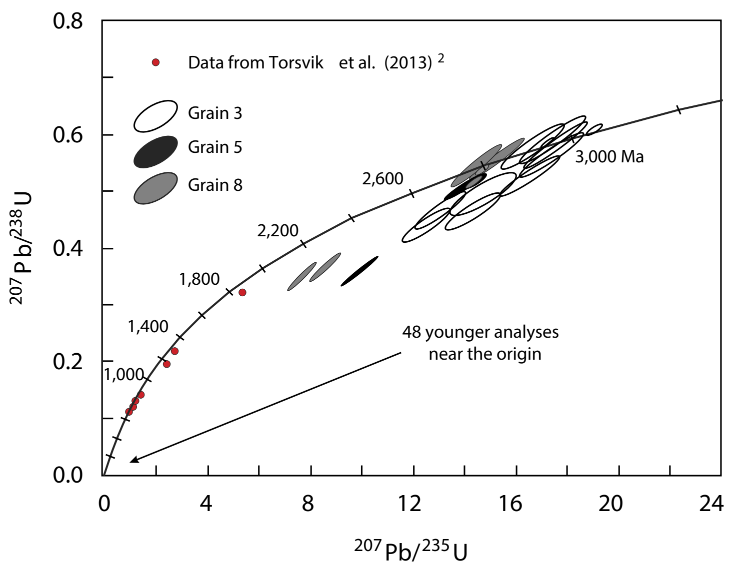


Fig. 5: Concordia plot that includes all 20 data points from three Archean zircons (the vertical axis should be $^{206}Pb/^{238}U$). The ellipses indicate the 1 s.d. analytical uncertainties for each of the SIMS determinations. Also shown as red symbols are the ages reported by Torsvik et al. (2013) for eight Proterozoic zircons recovered from Mauritian basaltic beach sands. Tick marks on the Concordia curve are in Ma.

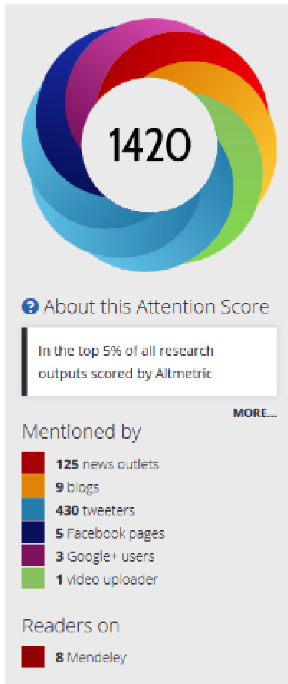
that trachytic magma traversed through and incorporated silicic continental crustal material that preserves a record of several hundred million years of Archaean evolution.

Ten of the 13 grains differ from the older zircons in that they are featureless, with no internal visible structures. These were determined to have late Miocene U–Pb systematics with no traces of inherited components, yielding a mean age of 5.7±0.2 Ma (crystallization age of the trachyte magma).

Our findings confirm the existence of continental crust beneath Mauritius and document, for the first time, the presence of Archaean zircons as xenocrysts in young volcanic rocks from ocean basin settings. We propose that Mauritius and other potential Mauritian continental fragments, collectively named "Mauritia" (Fig. 6), are dominantly underlain by Archaean continental crust, and formed part of the ancient nucleus of Madagascar and India. Conversely, the Seychelles (and probably also the Laxmi Ridge, Fig. 1) is likely underlain by Palaeoproterozoic rocks (Shellnutt et al. 2015. Geophys. Res. Lett. 42, 207–10,215), as in northern Madagascar, but was later affected by extensive Neoproterozoic arc magmatism.

The long-lost continent of "Mauritia" attracted massive international interest in the popular press when first published in 2013, but because that study was based on zircons from basaltic beach sand it was also criticized by some scientists

Since this study *"established"* continental crust beneath Mauritius, we were stunned by the media attention that the paper attracted. Whilst the 2013 paper has an Altmetric score of 331 (after 4 years), our latest paper scored 1420 in 6 days; the highest recorded in *Nature Communications* and in the top 5% of all research outputs scored by Altmetric.



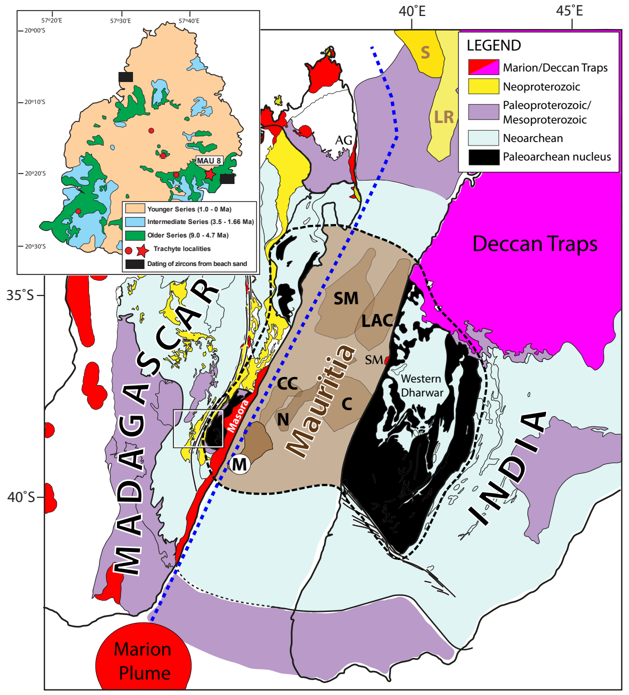


Fig. 6: Simplified geology of Madagascar and India reconstructed to 90–85 Ma. Mauritius (M) is reconstructed in a likely location near Archaean–Neoproterozoic rocks in central-east Madagascar just prior to break-up. The exact size and geometries of Mauritius and other potential Mauritian continental fragments (collectively known as Mauritia, including SM Saya de Malha; C, Chagos; CC, Cargados-Carajos Banks; LAC, Laccadives; N, Nazreth; see Fig. 1) are unknown. We propose that Mauritia is dominantly underlain by Archaean continental crust, and part of the ancient nucleus of Madagascar and India (stippled black line). A Large Igneous Province event (linked to the Marion plume) occurred from 92 to 84 Ma, and most of Madagascar was covered with flood basalts (full extent not shown for simplicity). Blue stippled line indicates the site of Cretaceous pre-breakup strike-slip faulting. LR, Laxmi Ridge; S, Seychelles. *Inset map* shows simplified geology of Mauritius, including trachyte plugs. Star symbol marked MAU-8 is the sampling area for the present study and black rectangles indicate locations of zircons recovered from beach sand samples in the 2013 study.

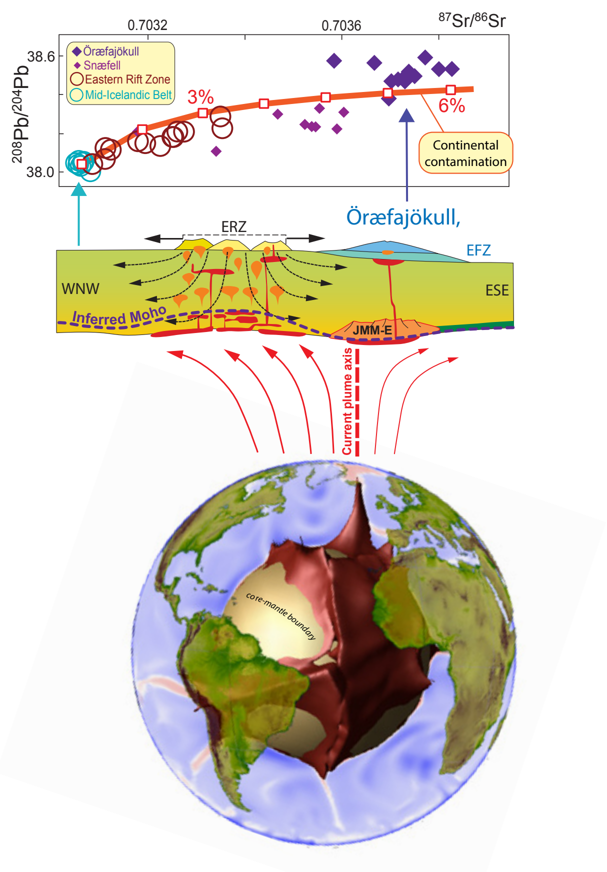
Paper 3

Torsvik, T. H., Amundsen, H.E.F., Trønnes, R.G., Doubrovine, P., Gaina, C., Kusznir, N.J., Steinberger, B., Corfu, F., Ashwal, L.D., Griffin, W.L., Werner, S.C., Jamtveit, B. 2015. Continental crust beneath southeast Iceland. ***Proceedings of the National Academy of Sciences of the United States of America***. DOI: 10.1073/pnas.1423099112.

The thick crust of Iceland and the surrounding Iceland plateau is generated mainly by accumulation of young magmatic rocks and is therefore oceanic in nature. Geochemical and geophysical data, however, indicate that fragments of continental crust are also present beneath the southeast coast of Iceland. In this paper – through modelling of Sr–Nd–Pb abundances and isotope ratios – we suggest that a continental sliver representing a south-western extension of the Jan Mayen Microcontinent are deeply buried under a thick pile of volcanic rocks.

Iceland and the surrounding plateau, straddling the Mid-Atlantic ridge, are lifted above sea level by a light and hot column of rocks (mainly peridotite), flowing slowly upwards from the Earth's deep interior (Fig. 7). The low-density hot rocks in the plume undergo partial melting near the surface due to pressure release, resulting in high magma supply to the Icelandic rift zones and their flank zones. This leads to thick oceanic crust under the shallow plateau and subaerial (Iceland) part of the northeast Atlantic. Recent estimates of the Iceland plume flux of 40-60 km³/year indicate that it might be 4-10 times that of the Hawaii plume flux (Jones et al. 2014. Earth Planet. Sci. Lett. 386, 86-97). Therefore, the current Iceland plume seems to be the Earth's most vigorous plume.

Fig. 7: Numerical model of chemical convection in Earth's mantle (courtesy of Abigail Bull-Aller) showing a large compositionally distinct structure in the present-day mantle beneath Africa (red material). Plumes rise from the edges of this structure and magmatic activity in Iceland is linked to such a plume, which has been active for the past 62 My. However, some lavas contain continental material (higher $^{87}Sr/^{86}Sr$ and $^{208}Pb/^{204}Pb$ ratios, and especially also higher $^{207}Pb/^{204}Pb$ ratios), previously proposed to have been recycled through the plume. Torsvik and collaborators (from Norway, Germany, UK, Australia and South Africa) maintain that the plume split off a sliver of continent (Fig. 8) from Greenland ~50 My ago. This sliver — probably an extension of the Jan Mayen Microcontinent — is now located beneath southeast Iceland (JMM-E) where it locally contaminates some of the plume-derived magmas.



Our inference that deeply buried fragments of continental crust occur beneath southeast Iceland is based on reconstructed movements of the Eurasian-Greenland (North-American) plates and the Jan Mayen Microcontinent – during and after opening of the northeast Atlantic 54 million years ago – and evidence that the southeast Iceland crust is especially thick (Fig. 8). The model is supported by the chemical composition of lavas erupted in the Eastern Rift Zone (ERZ) and from the Öræfajökull and Snæfell central volcanos in the Eastern Flank Zone (EFZ) of Iceland. In particular, the isotope ratios of the elements Sr, Nd and Pb in the lavas of the ERZ and EFZ, define a continental crust contamination trend, with up to 6% contamination in some of the Öræfajökull rocks (Fig. 7).

The realization that continental fragments may be buried under southeast Iceland provides new insights into the complex evolution of the northeast Atlantic, in particular, and into the interaction of deep mantle plumes with continental break-up, plate separation and rift jumps, in general. There are several examples of such interactions in the Tethys and Indian Ocean domains during the break-up and dispersion of the Pangea supercontinent, especially related to the separation of India, Australia, Africa and Antarctica. In **Papers 1 and 2** we have reported the discovery of Precambrian zircon xenocrysts in basalts from Mauritius, pointing to hidden continental crust also beneath that ocean island. Intraoceanic continental fragments appear to be much more abundant than previously thought and caution is therefore recommended in interpreting (enriched) geochemical signatures in ocean island basalts.

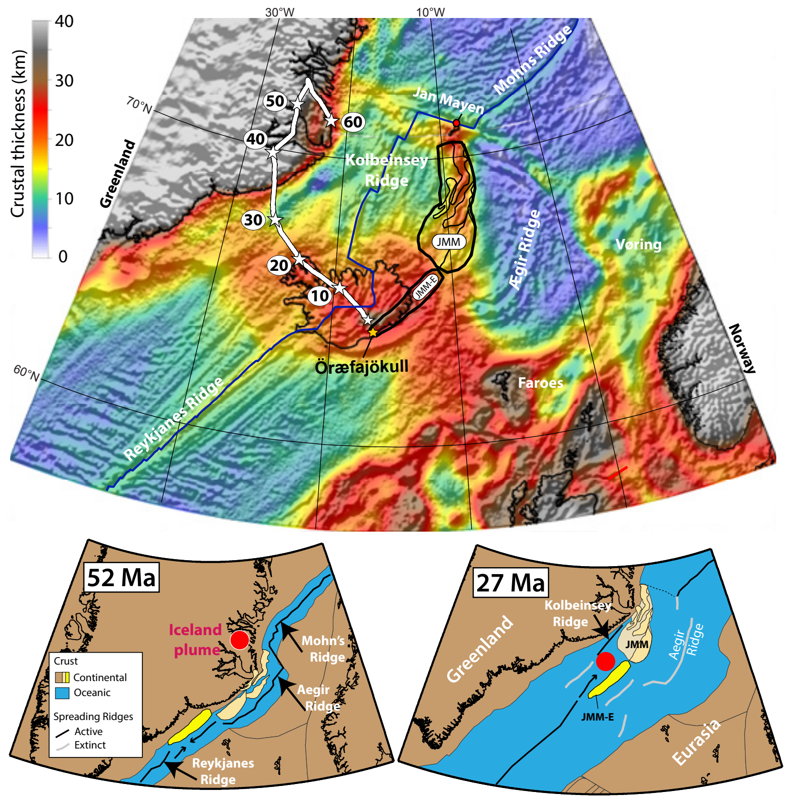


Fig. 8: Crustal thickness map based on gravity inversion and location of the Iceland plume (white star symbols in 10 My intervals) relative to Greenland back to 60 Ma. The 'classic' Jan Mayen Microcontinent (JMM) is ~500 km long (shown with four continental basement ridges), and crustal thicknesses are ~18-20 km. In this study, Torsvik and collaborators extend JMM 350 km south-westwards beneath southeast Iceland (JMM-E), and calculate maximum crustal thicknesses of ~32 km. The lower panels show plate reconstructions at 52 Ma (shortly after initiation of seafloor spreading) – and at 27 Ma – when the Ægir Ridge was abandoned and JMM and JMM-E permanently became part of Eurasia.

II. TALES FROM TWO CONTINENTAL MARGINS – A WILSON CYCLE APART

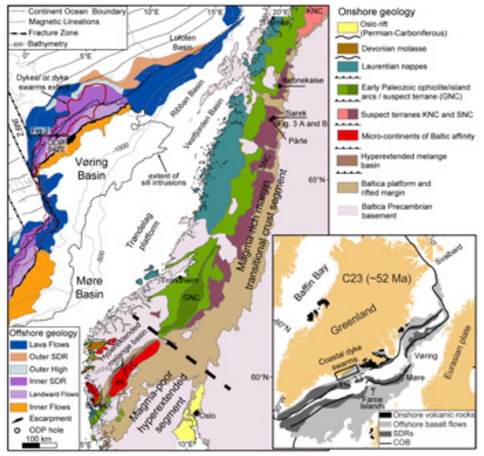
With the Abdelmalak et al. paper, published in **Geology**, a team of seven CEED geologists and geophysicists working in the Dynamic Earth and Earth Crisis research groups integrated their observations and detailed knowledge from onshore geology in the Scandinavian Caledonides with that of the offshore Norwegian Sea Shelf. Because of the excellent cross-disciplinary communication established by the CEED organization and localisation, and the financial resources available for expedition type field-studies, we quickly established that the deeper levels of an ancient ocean-continent transition zone in a fossil magma-rich passive margin was available for direct and detailed observations, mapping and sampling within the Caledonides. By comparing details from on- and off-shore observations, we have established that a nearly 1000 km long transect in the Caledonides is a 'world-class' ancient (600 Ma) analogue to modern ocean-continent transitions (OCT) and associated large-igneous provinces (LIPS). The onshore OCT analogue in Scandinavia reveals spectacular intrusive relationships between continental margin sediments, extended crystalline basement and basaltic dyke-swarm systems, which in present-day margins are concealed by large thicknesses of water and sediment. The results of this research are already well cited and presented at a number of scientific meetings. It has also resulted in additional NFR-funding through the curiosity-driven research and highly competitive FRINATEK program in a new (2016-2019) CEED project: "Hyperextension in magma-poor and magma-rich domains along the pre-Caledonian passive margin of Baltica".

Paper 4

<u>Abdelmalak, M.M., Andersen, T.B., Planke, S., Faleide, J.I., Corfu, F.,</u> Tegner, C., <u>Shephard, G.E., Zastrozhnov, D.,</u> and R. Myklebust, **2015**, The ocean-continent transition in the mid-Norwegian margin: Insight from seismic data and an onshore Caledonian field analogue. ***Geology***, *43*(11), 1011-1014.

Passive continental margins may be very complex geological provinces indeed, including features like intense ductile to brittle deformation accompanied by high temperature-low pressure metamorphism and tectonically controlled sedimentation. In addition, the widespread association with large volumes of break-up-related magmatic rocks, sometimes forming large igneous complexes, is another factor that complicates our understanding of these geological provinces. Exposed Ocean-Continent Transition (OCT) have contributed significantly to understanding hyper-extended margin development. Several studies have been addressed to the magma-poor margin analogues, but less is known about the magma-rich margin analogues. These margins are characterized by the presence of Seaward Dipping Reflectors (SDR), an intense network of mafic sheet intrusions in the continental crust and adjacent sedimentary basins and a high-velocity (Vp> 7.0 km/s) lower crustal body (LCB). Most of the present-day magma-rich margins are submerged offshore and are therefore difficult to study by direct observation. Furthermore, the thick accumulation of extrusive and intrusive rocks presents a major challenge for seismic imaging of deeper levels. These issues have led to uncertainties in the interpretations of margin evolutions and their structure, in particular, details of the transitional crust located beneath the SDR. In such situations, better seismic resolution combined with studies of field analogues can improve our understanding of the OCT in magma-rich margins. In this paper we presented new mapping results of the breakup related igneous rocks on the Mid-Norwegian margin using high-quality and reprocessed multichannel seismic data as well as results from drill core 642E. Below the SDR, vertical and inclined reflections are interpreted as the dyke swarm feeder systems. Different high-amplitude reflections with abrupt termination and saucer shaped geometries are interpreted as sill intrusions. The identification of saucer shaped sills implies the presence of sediments in the transition-zone beneath the volcanic sequences.

In this study, our team of authors include applied marine geophysicists with widespread experience from present-day continental margins and geologists with experience from mountain-belts which have joined forces in combining new observations from the well-exposed field analogue in the Seve Nappe Complex (SNC) in the Scandinavian Caledonides with the transitional crust located beneath the SDR of the Mid-Norwegian margin. The SNC was first suggested to be an analogue of a distal magma-rich continental margin in the 1990-ies (see references in manuscript), but this aspect of the SNC has since been largely ignored before our new cross-disciplinary research effort. An important characteristic of the SNC is the abundance and spectacular exposures of meta-basaltic composite dyke



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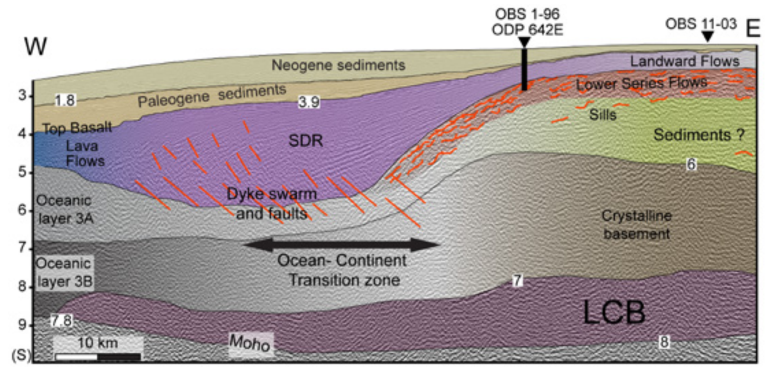

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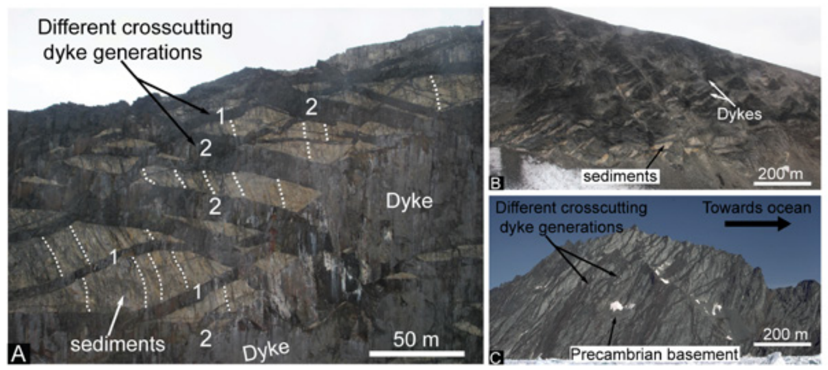


Fig. 9a. Present day map of the Vøring margin, Norway, with inset map showing its position before break-up occurred between Europe and Greenland. **b.** Seismic cross-section showing present-day magma-rich passive margin along the Vøring margin high. **c.** Dyke intrusions into the old Baltican passive margin (Seve Nappe Complex (SNC)

complexes truncating continental basement and cover units. The host-rocks for the dykes are mainly hornfelsed sediments with a preserved stratigraphic thickness of up to ~5 km. The field analogues represent an onshore analogue to the deeper level of the Mid-Norwegian margin, permitting direct observation and sampling and providing an improved understanding particularly of the deeper levels of present-day magma-rich margins.

We consider the results of our cross-disciplinary work to be of widespread interest to the geoscience community, because distal parts of continental margins worldwide are the subject of intense academic research and petroleum exploration. Research in progress will provide a number of details on the SNC later; here we presented the first account of an on-going cross-disciplinary research effort, which will improve the understanding of the structure and evolution in magma-rich passive continental margins.

Fig. 10. Fur Island in Denmark is a key target for several ongoing projects in the Earth Crises group. The black layers represent tephras deposited during the initial Eocene following explosive volcanic eruptions on Greenland and west Norway and UK (the North East Atlantic igneous province).

III. LARGE IGNEOUS PROVINCES AND PALEOCLIMATES

One of the CEED objectives is to "Understand the role of voluminous intrusive and extrusive volcanism on global climate changes and extinctions in Earth history", to cite the CEED's RCN proposal. The group activities involve both studies of volcanic and metamorphic processes in Large Igneous Provinces, and proxy data from sedimentary deposits. During the first 3.5 years of CEED, we have published papers on topics such as the Cambrian SPICE event, global carbon and sulfur cycles, Paleocene tephra chronology, and the Paleocene-Eocene Thermal Maximum (PETM; see Fig. 10). In addition, we have had many projects in the Siberian Traps region in order to further investigate the role of volcanism in the end-Permian mass extinction and climatic change.

Paper 5:

Stordal, F. Svensen, H.H., Aarnes, I., and Roscher, M. 2017. Global temperature response to century-scale degassing from the Siberian Traps Large Igneous Province. ***Palaeogeography, Palaeoclimatology, Palaeoecology,*** 471, 96-107.

One of the key group activities is to develop better degassing models for LIPs and to evaluate the climatic consequences. In this paper, we have calculated the temperature responses following several degassing scenarios in the Siberian Traps. The paper is first-authored by Frode Stordal, a CEED-associated professor at the Department of Geosciences in Oslo.

If the Siberian Traps were wholly or partially responsible for the end-Permian crisis, release of gases must have taken place on a timescale tuned to the cooling of lava flows and sub-volcanic intrusions (i.e. decades to centuries) – and that release must have been sufficient to affect the atmospheric chemistry. However, previous work on the end-Permian has not considered the climatic effects of large

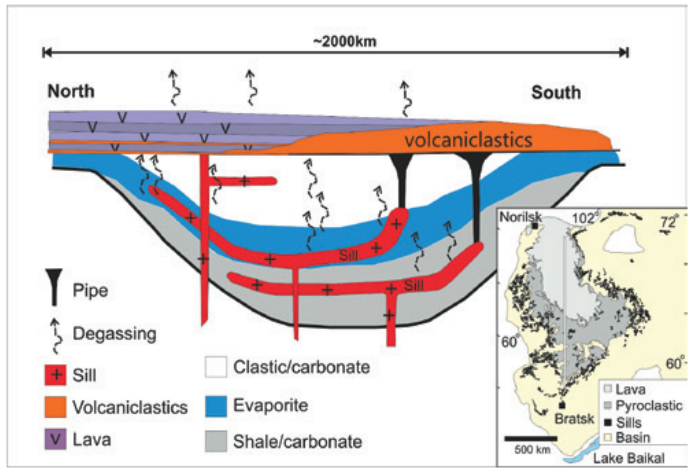


Fig. 11. Schematic north-south cross section of the Siberian Traps showing the two dominant sources of carbon gas: 1) mantle carbon from basalts, and 2) sedimentary carbon from contact aureoles around sub-volcanic sills. The sedimentary carbon was partly degassed from pipe structures rooted in contact aureoles (Svensen et al., 2009a). The figure is modified from Jerram et al. (2016).

scale single events. We have used a simple box model to constrain century-scale degassing of CO_2 and CH_4 from high-end volumes of individual lava flows and sills from the Siberian Traps. The model includes gas fluxes of CH_4 and CO_2, their atmospheric lifetimes and radiative forcing, as well as the climate sensitivity in a global average climate system calibrated to end-Permian time. The fluxes are estimated based on lava degassing and contact aureole volumes and devolatilization during the first 100 years following sill emplacement. Fig. 11 is a schematic overview of degassing systems in the Siberian Traps.

We tested the sensitivity to extreme emissions of up to 25 GtC/yr, CH_4 fractions from 0 to 100 %, wide ranges of climate sensitivities (1.5-6.0 °C for CO_2 doubling), pre-event concentrations, and atmospheric lifetimes. We find that the global annual mean temperature perturbation is 7.0 °C in a baseline case using a 10 GtC/yr emission and a 60 % CH_4 fraction (4.5 °C as the climate sensitivity) (Fig. 12). Even for low emission scenarios (0.7-1.2 GtC/yr), the temperature response is more than 1.5 °C.

We conclude that sporadic individual large-scale volcanic events in Large Igneous Provinces have the potential to cause a strong global warming on very short timescales. In addition to the emission strength, the CH_4 fraction and the climate sensitivity have the strongest impact on the century-scale temperature perturbation.

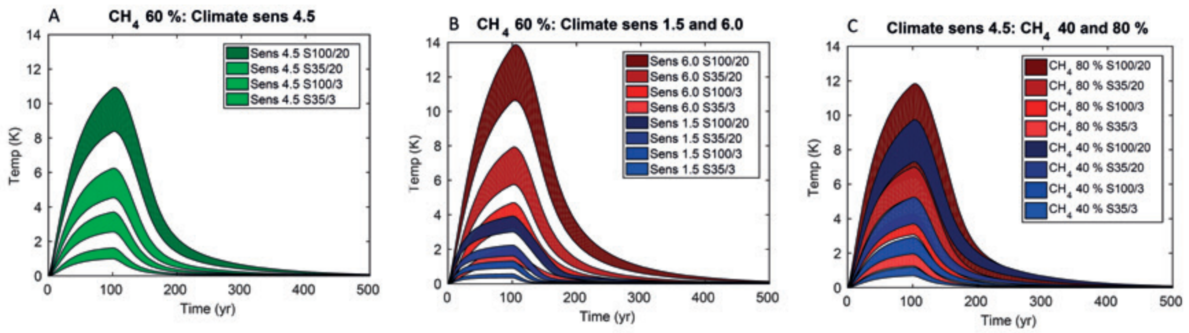


Fig. 12 Time evolution of ranges temperature perturbations (K) encompassing four different emission scenarios. Results are given for (A) a baseline case, (B) climate sensitivities 1.5 and 6.0, and (C) CH_4 fractions 40 and 80 %. From Stordal et al. (2017).

IV. LINKING SURFACE TECTONICS and VOLCANISM to the DEEP EARTH

Paper 6

Torsvik, T.H., Van der Voo, R., Doubrovine, P.V., Burke, K., Steinberger, B., Ashwal, L.D., Trønnes, R., Webb, S.J., Bull, A.L. **2014**. Deep mantle structure as a reference frame for movements in and on the Earth. ***Proceedings of the National Academy of Sciences of the United States of America*** 111, 24, 8735–8740.

CEED's mission is to develop a model that links plate tectonics and surface volcanism with processes in the deep mantle. This paper links a new model for plate motion for the last 540 My with deep mantle structures identified from present day geophysical data. Previous studies by some of the current CEED-based researchers (Torsvik and Steinberger) have gathered strong evidence that the deep mantle structures (see below) have remained stable for at least 300 My, and there is strong circumstantial evidence that the stability have lasted much longer. The new plate reconstruction reveals how Earth's mass has been re-distributed through time and led to true polar wander (TPW). This absolute kinematic model suggests that Earth had a degree-2 mantle convection mode at least since 540 Ma. The findings are also important for understanding Earth's past climate variations due to tilting of its axis. The core expertise needed for this study belongs to CEED researchers (paleomagnetism and plate tectonics-Torsvik, Doubrovine; mantle convection and geodynamics-Steinberger and Bull; petrology of deep mantle-Trønnes) who set the research task: **Absolute reference frames and links to the deep mantle** (Sub-theme 1.1).

Since the Pangea supercontinent formed about 320 million years ago, plumes that sourced LIPs and kimberlites have been derived from the edges of two stable thermochemical reservoirs at the core–mantle boundary (Fig. 9). In this paper we tested whether it was possible to maintain this remarkable surface to-deep Earth correlation before Pangea through the development of a new plate reconstruction method and found that our reconstructions for the past 540 million years comply with known geological and tectonic constraints (opening and closure of oceans, mountain building, and more).

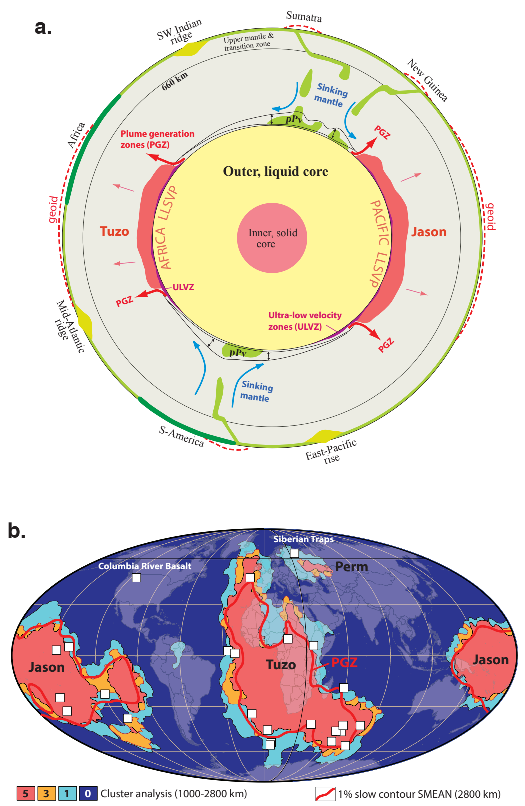


Fig. 13: (**a**) Schematic cross-section of the Earth as seen from the South Pole. The Earth's lower mantle is dominated by two antipodal large low shear-wave velocity provinces (LLSVPs) beneath Africa (Tuzo) and the Pacific (Jason). These dominate the elevated regions of the residual geoid (dashed red lines), and their margins, the plume generation zones (PGZs), are the principal source regions for LIPs and kimberlites. The thin arrows above Tuzo and Jason are shown to indicate that the residual geoid is largely a result of buoyant upwellings overlying these hot and dense mantle structures. (**b**) Reconstructed LIPs for the past 300 My and the 1% slow SMEAN contour (2,800 km depth) used as a proxy for the plume generation zones. Also shown are seismic "voting" map contours. Contours 5–1 (only 5, 3, and 1 are shown for clarity) define Tuzo and Jason (seismically slow regions) in addition to a smaller Perm anomaly. The Columbia River Basalt (17 Ma) is the only anomalous large igneous province (located above faster regions, contour 0) in these global tomographic models.

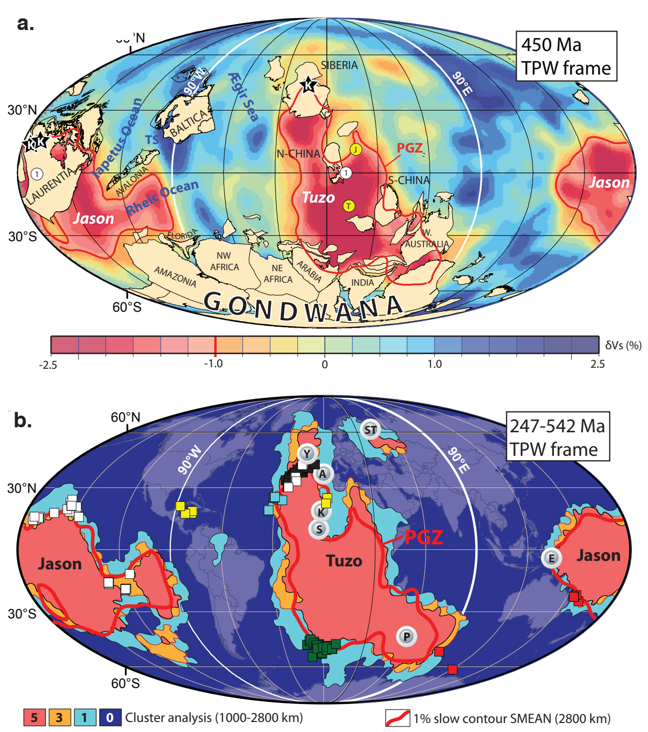


Fig. 14 (**a**) 450 Ma true polar wander (TPW)-corrected mantle frame reconstruction draped on the SMEAN tomographic model and the plume generation zones (PGZs; 1% slow SMEAN contour). Yellow dots (marked T and J) are the center of mass for Tuzo and its antipode for Jason. Open white circles (marked 1) show the preferred axis (0°N, 11°E and 169°W) for Palaeozoic TPW and approximate the longitude of the minimum moment of inertia (I_{min}) axis associated with the Tuzo and Jason large low shear-wave velocity provinces. Kimberlite locations (Canada and Siberia, black stars) dated to 445–455 Ma fall vertically above the plume generation zones. (**b**) Palaeozoic LIPs (annotated grey circles with white rings; 251–510 Ma) and kimberlites (coloured and black and white squares; 247–542 Ma) reconstructed in a TPW-corrected reference frame to the exact eruption time (sixth and final iteration). Kimberlites are plotted with white (Laurentia), yellow (Baltica: Russia), black (Siberia), light blue (China blocks), green (Gondwana: South Africa), and red (Gondwana: Australia) colors. K, Kalkarindji (510 Ma, Australia); A, Altay-Sayan (400 Ma, Siberia); Y, Yakutsk (360 Ma, Siberia); S, Skagerrak (297 Ma, Europe); P, Panjal Traps (285 Ma, India/NW Himalaya; allochthonous); E, Emeishan (258 Ma, South China); ST, Siberian Traps (251 Ma). Background map as in Fig. 13b.

The Early Palaeozoic was dominated by the great continent of Gondwana. Other continents included Laurentia and Baltica (Fig. 13a), which fused together with the Avalonia microcontinent to form Laurussia, the second largest Palaeozoic continent, after the closure of the Iapetus Ocean (~430 Ma). At around 320 Ma, Gondwana and Laurussia had amalgamated, forming the supercontinent of Pangea. Relative fits within Gondwana, Laurussia, and later, Pangea are reasonably well known. In contrast, absolute Palaeozoic reconstructions have remained uncertain because longitudes of continental blocks cannot be derived from paleomagnetic data (although latitudes and azimuthal orientations can). Palaeogeographic reconstructions relate the past configurations of continents to the Earth's spin axis. However, correlating the reconstructed positions of LIPs and kimberlites to the plume generation zones requires reconstructions relative to the Earth's mantle.

To define the longitudes in our palaeogeographic reconstructions, using the correlation between the eruption localities of LIPs/kimberlites and the plume generation zones, we adopted a novel approach, incorporating the estimates of TPW. For our initial model, continental longitudes in the paleomagnetic frame were defined both according to geological constraints and so that LIPs or kimberlites were located directly above a plume generation zone, ignoring any possible TPW (and plume advection) in the Palaeozoic. The next step from this idealized model was estimating TPW and correcting the palaeogeographic reconstruction, using the obtained TPW rotations. The method we used to derive the TPW rotations requires that the longitudes of the continents in the paleomagnetic frame are specified before estimating TPW. Because these are a priori unknown, we developed

an iterative approach for defining a paleomagnetic frame, corrected for TPW. Using our initial idealized Palaeozoic reconstructions with no TPW, we computed net rotations of continents at 10 My steps, which were decomposed into component rotations along three orthogonal axes. Axis 1 is at the equator at 11°E, which corresponds to the longitude axis of minimum moment of inertia of Tuzo and Jason (Fig. 13a). Episodes of coherent rotations about this axis were interpreted as a TPW signal (i.e., we assume that a dominant contribution from the stable large low shear-wave velocity provinces to the overall moment of inertia of the Earth stabilizes the orientation of the TPW axis over geologic time). Because the TPW corrections would generally degrade the large igneous province and kimberlite fits to the plume generation zones, the longitudes in the paleomagnetic frame were then redefined to produce an optimal fit after the TPW correction. This produced the second approximation for the longitude-calibrated paleomagnetic frame. The entire procedure of TPW analysis and longitude refinements was repeated six times until no further improvement was observed in the TPW-corrected frame.

In this paper – with the procedures and assumption described above – we produced the first longitude-calibrated Palaeozoic reconstructions. In the TPW-corrected frame, five of seven Palaeozoic LIPs plot within 5° of the plume generation zones, and one (Panjal Traps) plots 11.2° away. Of 231 kimberlites, 98% plot within 10° of a plume generation zone. Although our longitude-fitting method used the 1% slow SMEAN contour as a proxy for the plume generation zones, the statistical correlation is similar and even improved compared with the seismic voting map contours. As an example, all LIPs (including the Siberian Traps) plot within 10° of contour 4 (Fig. 13b).

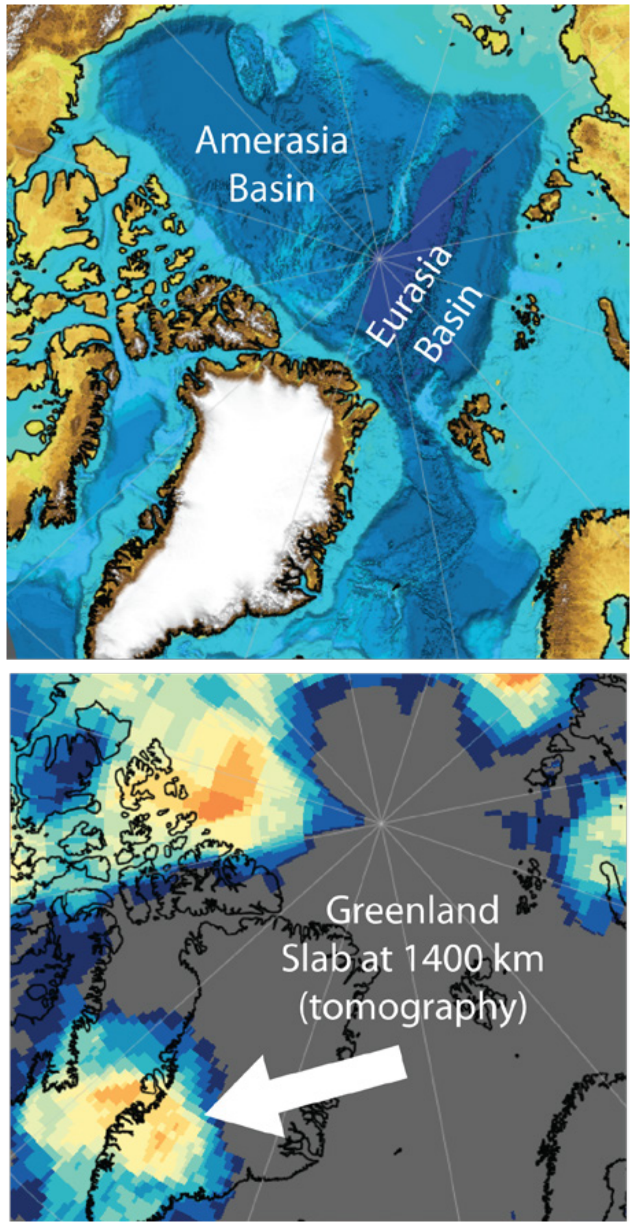


Fig. 15. Top panel shows surface overview of Arctic region with two major oceanic basins. Bottom panel shows mantle view based on a collection of tomography models with the Greenland slab location (blue-yellow colours) at 1400 km depth.

Paper 7

Shephard, G., R. Trønnes, W. Spakman, I. Panet, and C. Gaina. **2016.** Evidence for slab material under Greenland and links to Cretaceous High Arctic magmatism. ***Geophysical Research Letters***, 43, doi:10.1002/2016GL068424.

In the global puzzle of reconstructing continents and oceans through deep time, the Arctic remains one of the most challenging and controversial regions. Today, the Arctic Ocean consists of two basins, the large "Amerasia Basin" and the smaller and younger "Eurasia Basin" (Fig. 15), which are surrounded by the major tectonic plates of North America and Eurasia. However, this has not always been the geographical configuration. Over the last several millions of years, the Arctic has also undergone turbulent history of ocean basin opening and closure, mountain building events and massive magmatic eruptions. Understanding the geological complexity of the region is further compounded at present-day by challenging climatic conditions and remoteness for sampling. The study by Shephard et al. (2016) highlighted the power of integrating several geological and geophysical datasets, including those from earthquakes, satellite measurements of gravity and geochemical signatures of volcanic rocks. The study was able to link key lines of evidence in time and space to a specific feature found deep below Greenland, that had previously been only looked at in isolation.

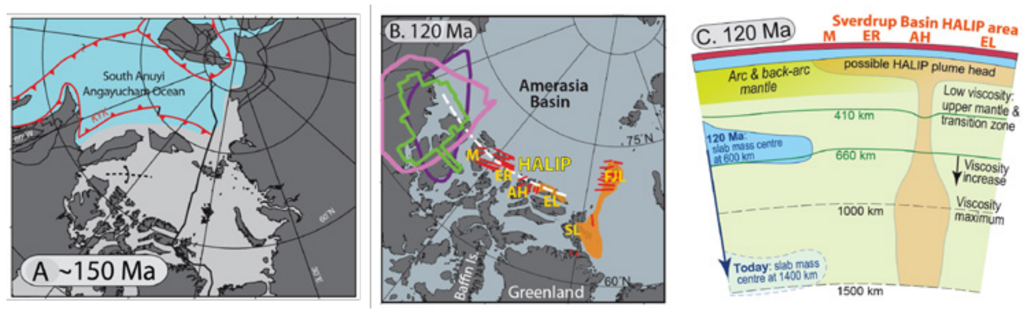
Furthermore, the success of this study and the scale of the datasets used, relied on a close collaboration between internal CEED researchers Reidar Trønnes, Carmen Gaina and Grace Shephard and international partners, Isabelle Panet from Paris Diderot, and Wim Spakman from Utrecht University/CEED.

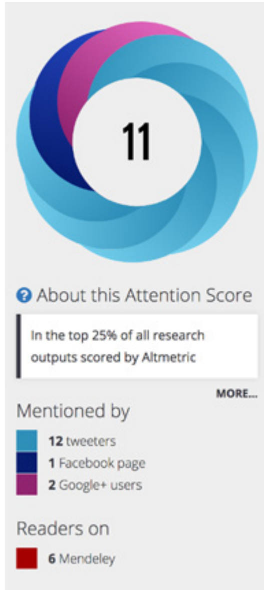
Seismic tomography, similar in principle to the medical tomography scans that are used to image the human body, is one of the foremost datasets that reveals an insight into the internal structure of Earth today. Regions of fast seismic wavespeeds are often interpreted as cold and old subducted slabs of long-lost oceans. Different tomography models reveal possible slabs peppered throughout the Earth's mantle, and one such feature is located around 1000-1400 km below Greenland today (Fig. 15). However, if this seismic anomaly represented an extinct ocean basin, it begged the questions: which ocean does this feature reveal, why and when was it subducted, and can we see its signature in other datasets?

Through a careful analysis, the study revealed that when the Amerasia Basin opened, it contemporaneously closed another ocean, called the South Anuyi Ocean, which oceanic lithosphere subducted around 160-120 Million years ago. This explains why it is at a mid-mantle depth today, having descended near vertically through the mantle. It was demonstrated that the seismic anomaly could also be independently verified with a signal in the satellite-derived gravity gradients. Significantly, the paper linked the existence of the slab to the massive Cretaceous High Arctic Large Igneous Province (HALIP). The HALIP was formed by an extensive volcanic episode around 120 million years ago in the oceans and surrounding continents, such as Svalbard and the Canadian Arctic Islands. The arc mantle from the subducting slab of the South Anuyi Ocean may be manifested in the geochemical signature of the western part of the HALIP. This study suggests a novel addition to the "mantle plume" eruption model which has generally been suggested as the cause and signal of the volcanic rocks.

In addition, the study provided the inspiration for a current research project that creates a "vote" map of different tomography models, like for the Greenland slab, but across 14 different models. This is an initiative of the first author, with an objective to engage other early career researchers, from CEED and the University of Oxford (Shephard, Matthews, Hosseini and Domeier, in preparation).

Fig. 16. Adapted from Shephard et al., 2016. Panel A: Plate reconstruction at 150 Ma (Million years ago) showing the configuration of the South Anuyi Ocean prior to opening of the Amerasia Basin. B: Location of the HALIP eruption sites (orange and red) compared to the slab location to the west (pink, purple, green contours) at 120 Ma. C: Vertical slice showing interaction of plume idea and the subducted slab at 120 Ma.





V. THE STRUCTURE AND DYNAMICS of the D”-ZONE in the DEEP EARTH

Paper 8

Mohn CE & Trønnes RG, **2016**. Iron spin state and site distribution in $FeAlO_3$-bearing bridgmanite. **Earth Planet. Sci. Lett.** 440, 178-186

Movements in the Earth are governed by the phase relations and material properties of the mineral bridgmanite (**bm**), which constitutes about 65% of the entire mantle and 75% of the lower mantle. In the cooler regions of the D”-zone (the lowermost 200-300 km above the core-mantle boundary), **bm** undergoes a densifying phase transition to post-bridgmanite (**pbm**). Because **bm** has very high entropy, we expect and have observed a reverse transition back to **bm** at the highest temperatures close to the core-mantle boundary. Both **bm** and **pbm** have ABO_3-type perovskite structures with two cation sites, A and B (Fig. 17). In the main $MgSiO_3$ component Mg^{2+} and Si^{4+} occupy the A- and B-sites, respectively. In contrast to the small and regular B-site surrounded by six nearest-neighbour O-anions (octahedral coordination) with nearly equal O-Si bond lengths, the large A-site is very irregular. In **bm** the O-Mg bond lengths fall into five groups, as shown in Fig. 1 (Mohn & Trønnes, 2016). The commonly used reference to either 12- or 8-fold coordination polyhedra for the A-site cations may therefore be misleading.

Ab initio and experimental investigations of the site distribution of Fe^{3+} and Al and of the iron spin state in **bm** have yielded largely conflicting results for the pressure-temperature (p-T) conditions of the lowermost mantle. In a study of the most important substitutional component, $FeAlO_3$, Mohn & Trønnes (2016) demonstrated that high-spin Fe^{3+} and Al remain in the A- and B-sites, respectively, beyond the p-T conditions of the mantle. The large $Fe^{3+}_{A\text{-}HS}$ cations can persist to such high pressures because flexible O-Fe bonds enable adaptation to the irregular A-site. The O-$Fe^{3+}_{A\text{-}HS}$ bonds have considerable charge transfer and covalency, and the deviation from fully ionic character is 38%, compared to 14%, 19% and 18% for Mg_A, Si_B and Al_B, respectively. The **bm** crystal lattice has a very strong affinity for Al_B, charge balanced by Fe^{3+}_A. Because peridotites have considerable Al-contents and because Fe is dominantly ferrous in the upper mantle and transition zone, the formation of **bm** in material sinking beyond 660 km depth involves a redox reaction with exsolution of metallic Fe:

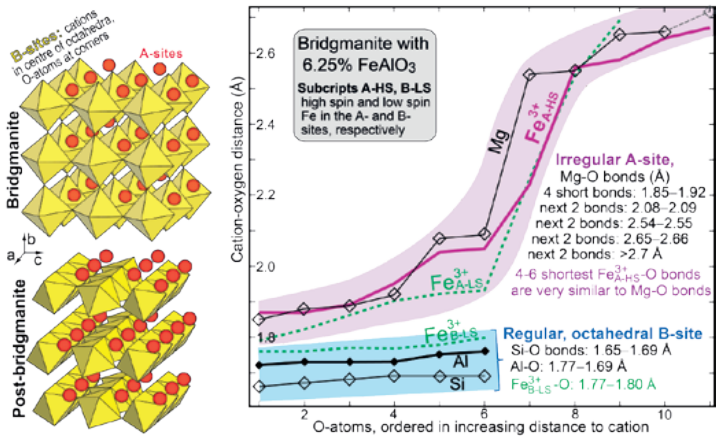


Fig. 17. Left panel: simplified depictions of the **bm** and **pbm** crystal structures. The octahedra are corner-linked in all three dimensions in **bm**, whereas the **pbm** structure involves edge-linking of the octahedra along the crystallographic a-axis and rigid sheet structures in the ac-plane. Compared to **bm**, the **pbm** structure is very compressible in the b-axis direction (normal to the sheets), resulting in a low bulk modulus, whereas the rigid ac-planes yield a high shear modulus. **Right panel**: variation in cation-oxygen distances for the A- and B-site oxygen coordination polyhedra in **bm**. Al fits very nicely into the regular octahedral B-site, whereas the flexible O-Fe bonds allows $Fe^{3+}_{A\text{-}HS}$ to adapt to the irregular A-site

$$\underset{\text{ringwoodite}}{2\ Fe_2SiO_4 + 2Mg_2SiO_4} + \underset{\text{garnet}}{Mg_3Al_2Si_3O_3} = \underset{\textbf{bm}}{2\ FeAlO_3 + 7\ MgSiO_3} + \underset{\text{ferropericlase}}{FeO} + \underset{\text{metal}}{Fe}$$

Based on a crystal chemistry survey of published **bm** analyses from basaltic and peridotitic mantle lithologies, Mohn & Trønnes (2016) concluded that such **bm** compositions mostly have $Al>Fe^{total}$. Therefore, the essential components in addition to $MgSiO_3$ are probably $FeAlO_3$, $FeSiO_3$ and Al_2O_3, in order of decreasing abundance. We have used ab initio computation to establish the partitioning of these components between **bm** and **pbm**, in order to understand how the seismic observations can be linked to mineral properties and the D” structure.”

Our preliminary results (Fig. 18.) show that the $FeSiO_3$ component partitions towards **pbm** with a distinct and wide phase loop, dipping towards lower pressures. Whereas both the $FeAlO_3$ and Al_2O_3 components seem to partition markedly towards **bm**, the energy differences between the coexisting phases are very small and the phase loops are flat and narrow. These features, which have prevailed during massive computational efforts over a three-year period, are consistent with the observed sharp D”-discontinuities in the high Vs longitudinal belt through the Arctic, Asia, Australia, Antarctica and the Americas. Our partitioning results indicate the following net chemical redox reaction for the bm to pbm transition:

$$\underset{\textbf{bm}}{2FeAlO_3+3MgSiO_3} + \underset{\text{metal}}{Fe} = \underset{\textbf{pbm}}{3\ FeSiO_3} + \underset{\text{mineral distribution according to lithology}}{Al_2O_3 + 3\ MgO}$$

In peridotitic lithologies the released MgO may increase the amount and the Mg/Fe ratio of ferropericlase and Al_2O_3 may dissolve in **pbm.** If **pbm** becomes Al-saturated, the Ca-ferrite structured phase (CF), with an $MgAl_2O_4$-component, may form. In basaltic material, an additional $MgAl_2O_4$-component will increase the amount of the pre-existing CF phase and the excess MgO may combine with free silica to increase the **pbm** proportion. The removal of metallic Fe by the **bm-pbm** reaction may induce oxidation of diamond to carbonate (magnesite), promoting small degrees of redox melting in the relatively cold subducted lithosphere, especially in basaltic lithologies. The **pbm** stability would expand in $FeSiO_3$-rich material, e.g. in possible Fe-rich magma ocean cumulates in the lower part of the LLSVPs. The effect of the elevated temperatures in the bottom layer of the LLSVPs, however, would destabilise the low-entropy **pbm** phase. A recent survey of the

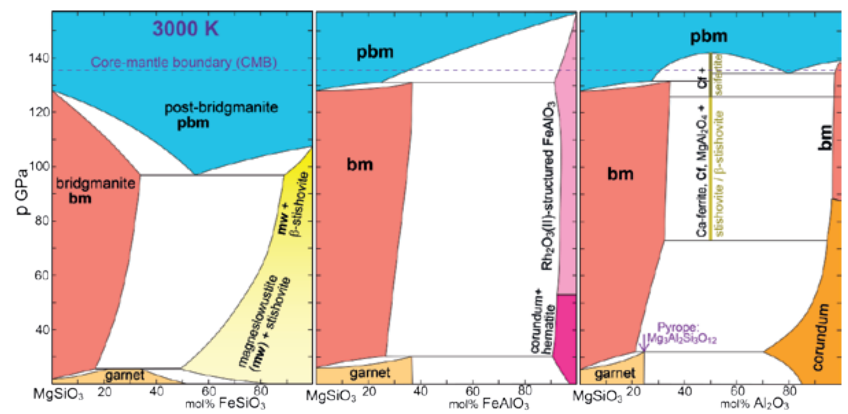


Fig. 18. Approximate phase relations in the three systems $MgSiO_3$-$FeSiO_3$, $MgSiO_3$-$FeSiO_3$ and $MgSiO_3$-Al_2O_3 at 3000 K and 20-150 GPa, based partly on Stixrude & Lithgow-Bertelloni (2011, GJI) and Mohn and Trønnes (preliminary data for the **bm-pbm** element partitioning).

seismic D" discontinuities concluded that such discontinuities are generally confined to the highvelocity regions outside the LLSVPs. The partitioning of $FeAlO_3$ and Al_2O_3 towards bm will in principle tend to destabilise **pbm** in basaltic material, which is enriched in these components. With the flat and narrow phase loops, however, this tendency will be counteracted by the low temperatures in subducted material entering the D" zone in the central parts of the high-velocity belt.

Our ongoing first-principles investigations of the phase relations, crystal chemistry and mineral physics of the major minerals in the lowermost mantle are essential for the clarification of several unresolved and very controversial issues. Better constraints on the material properties of the lower mantle, and especially of the D" zone, can improve the input parameters and lead to more realistic modelling of the flow pattern above the outer core surface and the core-mantle heat and chemical exchange.

VI. PLATE TECTONICS in the LATE PALEOZOIC

Paper 9

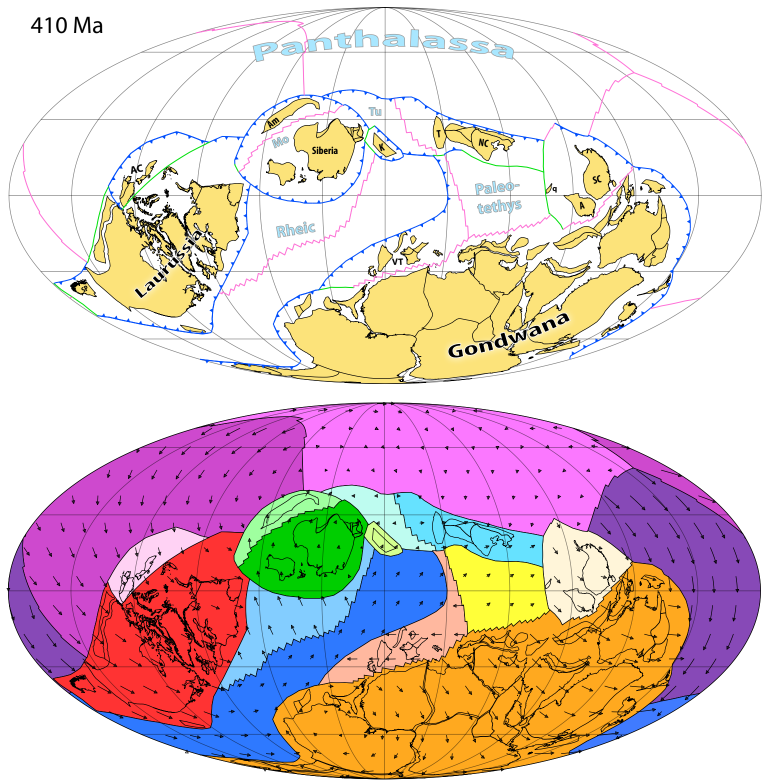
Domeier, M., and T. H. Torsvik. **2014**. Plate tectonics in the late Paleozoic, ***Geoscience Frontiers***, 5(3), 303-350.

Paleogeography is fundamental to our understanding of the history of plate tectonics and thus vital in efforts to link plate kinematics and mantle dynamics. Unfortunately, the relentless operation of subduction has obliterated Paleozoic and early Mesozoic oceanic lithosphere, making pre-Cretaceous 'full-plate' paleogeographic reconstructions exceptionally challenging. However, with the development of new geodynamic concepts and analytical tools, it is now feasible to construct, test and share such models, even though they can only be considered provisional. Here we present a global plate model for the late Paleozoic (410–250 Ma), together with a review of the underlying data and interpretations.

Mat Domeier, CEED postdoctoral fellow and YFF (Young Research Talent from RCN) awardee (from 2015) and co-author Trond Torsvik, built the first real plate tectonic model for the late Paleozoic by integrating geological observations and plate tectonic theory fundamentals. This is a significant and radical departure from the conventional approach of pre- Cretaceous palaeogeographic modeling, which continues to functionally operate under the framework of continental drift. As depicted in the 410 Ma reconstruction (Fig. 19), the new model includes explicitly delineated and meticulously managed plate boundaries, which allows the full spatio-temporal definition of tectonic plates, including those floored by oceanic lithosphere.

We trust that this model will be useful in extending the temporal reach of mantle models, but also hope that it may serve more broadly as a late Paleozoic tectonic framework for future testing and further improvement. So far, this is the highest cited paper from the selected papers presented here and **M. Domeier was awarded the Medal for the best paper published in Geoscience Frontiers in 2014.**

Fig. 19. Paleogeographic reconstruction showing simplified plate boundaries and labels of some major features.at 410 Ma (early Devonian). *Abbreviated continental units*: A, Annamia; AC, Arctic Alaska-Chukotka; Am, Amuria; Ch, Chilenia; K, Kazakhstania; NC, North China; q, South Qinling; SC, South China; SP, South Patagonia; T, Tarim; VT, Variscan terranes; *oceanic domains*: Mo, Mongol-Okhotsk Ocean; Tu, Turkestan Ocean. (B) Plate velocity field.



Major scientific results and research projects

Publication	Journal	**Journal Impact factor** 2015/2016 scijournal.org	**No. of citations/yr SCOPUS** (total/no years since publication)
Abdelmalak et al., 2015	Geology	4.55	2
Ashwal et al., 2017	Nature Communications	11.33	N/A
Domeier&Torsvik, 2014	Geoscience Frontiers	3.89	21.3
Mohn & Trønnes 2016	Earth and Planetary Science Letters	4.33	1
Shephard et al., 2016	Geophysical Research Letters	4.21	1
Stordal et al., 2017	Palaeogeography, Palaeoclimatology, Palaeoecology	2.59	N/A
Torsvik et al., 2013	Nature Geoscience	12.51	11
Torsvik et al., 2014	Proceedings of the National Academy of Sciences of USA	9.38	11.3
Torsvik et al., 2015	Proceedings of the National Academy of Sciences of USA	9.38	2.5

2013-2017 CEED publications in high impact journals

2 Nature (38.14*), 1 Nature Communications (11.33), 3 Nature Geoscience (12.51), 4 PNAS (9.38), 3 Science (34.66), 1 Science Advances, all-ca. 185 citations

* *Journal Impact factor 2015/2016 (scijournal.org)*

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