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Geodynamics, Geomagnetism and Paleogeography: A 50 Year Celebration

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REPORT

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Summary:

Prof. Dr. Trond Helge Torsvik was born on October 12, 1957. He attended the Norwegian Naval Academy before taking degrees from the University of Bergen in 1982 and 1985. In 1991, after a post-doctoral position at Oxford, Trond joined the Geological Survey of Norway in Trondheim, where he continues working today. Since then, he has also held appointments at the University of Bergen, the Norwegian University of Science and Technology, the University of Witwatersrand, and the University of Oslo. Trond is an Elected Fellow of the Royal Society of Norway, the Norwegian Academy of Science, the Academia Europea, and the American Geophysical Union.

Trond has made significant contributions in (among other sciences) paleomagnetism, paleogeography, plate tectonics, and mantle dynamics. His field areas have spanned the world's continents, and probed the Core Mantle Boundary. His list of collaborators is impressively international. Although his published contributions are legion, Trond is also well known for his paleomagnetic and plate reconstruction software, which he has consistently made available to the scientific community.

This seminar, *Geodynamics, Geomagnetism and Paleogeography: A 50 Year Celebration,* has been organized to honour Trond following the successful completion of his first half century. Statoil ASA, Physics of Geological Processes at the University of Oslo, and the Geological Survey of Norway are proud to sponsor these proceedings as a fitting recognition of the scientific contributions of THT.

Keywords: Paleogeography	Paleomagnetism	Mantle Dynamics
Trond	Helge	Torsvik
NGU	Statoil	PGP

Geodynamics, Geomagnetism and Paleogeography: A 50 Year Celebration

Sept. 21-22, 2007

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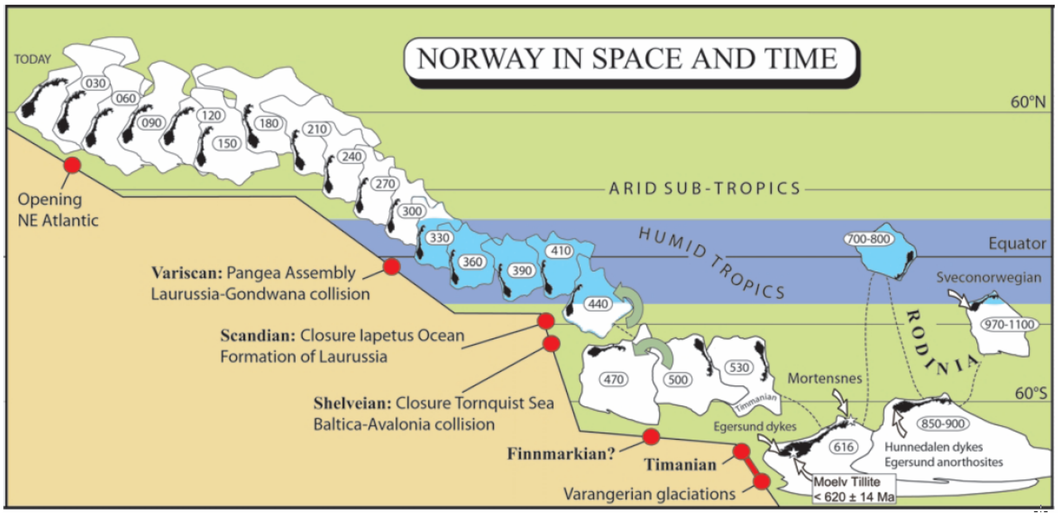
Sponsored by the Geological Survey of Norway, Statoil ASA, and Physics of Geological Processes at the University of Oslo.



Trond Torsvik, 2005

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THT, by Torgeir B. Andersen

1 PRINCIPIA

It is no simple accident that *Geodynamics, Geomagnetism and Paleogeography: A 50 Year Celebration* came to be. For more than a quarter century, Trond Helge Torsvik has wrestled with these topics. Along the way, his paths crossed with those of many earth scientists. Ensuing discussions and collaborations led to important and influential papers, on topics that varied between Precambrian paleogeography and Norwegian neotectonics. Yet throughout this onslaught of scientific contribution, Trond's efforts have remained remarkably focused. In some form or another, almost all of his work has dealt directly with the quantitative reconstruction of the geological past. Thus, as Trond approached fifty, his colleagues and friends chose to mark the occasion by arranging this seminar.

According to the American Heritage Dictionary, *PRINCIPIA* refers to a principle, especially a basic one. Used by Isaac Newton for his world-changing masterwork, the word conjures up images of a deep, fundamental, and encompassing knowledge. Plate tectonics, and the subsuming paradigm of mantle dynamics, have provided just such a unifying enlightenment for the earth sciences. No sub-discipline within geology or geophysics can hold itself immune from their clutches, and no geoscientist can successfully ignore them. Trond's lifetime devotion to his geological principia has borne many fruits, exemplified by this very congress. Throughout it all, he has managed to share his excitement in science with his colleagues, students, and friends, consistently enriching their lives.

TFR, SJHB, MAS
Trondheim, 2007

1.1 "I have only one objection!"

shouted a well-known California professor at a lecture on sea floor spreading in December, 1966. *"It violates every principle of geophysics!"*

The laws of geometry were deduced by the ancient Greek philosophers, whilst modern physics and chemistry were birthed by alchemists seeking the transmutation of lead into gold. By contrast, geology is a young science. It is difficult to define precisely the point in time when it passed from the realm of the miner seeking riches to a rigorous, self-correcting investigation of the Earth. However, it *is* possible to trace the origins of the idea that continents have moved ~ and in doing so, one may derive a profound appreciation of one's own individual link in the scientific chain.

Despite Eretosthenes' now-famous measures of the circumference of the Earth and the distance to the moon circa 276-194 BC, Europe of the Middle Ages remained woefully ignorant of the world around it. In 1406 a Latin translation of a Byzantine version of Ptolemy's *Geographica* was completed, but, even then, neither the sizes nor shapes of the continents were very well known. Cristóbal Colón sailed to the Americas on a diminutive, incomplete globe: contemporary geographers such as Martin Behaim placed China's coastline thousands of leagues too far to the east, and except for speculatively-placed, fancifully-named islands, no land barred his proposed progress to the riches of India. Yet less than one century later, the world map of Abraham Ortelius charted a South American coastline that matched surprisingly well with its African counterpart. It was an Age of Discovery, both geographically and intellectually. For it was the map of Ortelius that provoked Sir Francis Bacon to remark in 1620 that the strange similarities between these coastlines were *"no mere accidental occurrence."*

Though the general acceptance of continental mobility lay 350 years beyond Bacon, the geometrical similarities continued to tease. In 1858, Antonio Snider published a well-known set of engravings depicting the opening of the South Atlantic. His rationale was theological: publication of Darwin's Origin of Species and the subsequent showdown between Thomas Huxley and the Bishop of Oxford was yet to come. However, change came swiftly. By the turn of the previous century the natural sciences had been effectively liberated from restrictions imposed by fundamentalist religious authority, in no small part by geologists. Critical to this process was the steady accumulation of evidence for the longevity of the Earth. Perhaps not surprisingly, many of these very same climatic and paleontological data also became important factors in the acceptance of continental mobility.

In 1908, Frank Taylor proposed to the Geological Society of America that certain continents had not foundered in the ocean forming process, but rather had shifted horizontally. Taylor recognised the Mid Atlantic Ridge as the line of rifting between continents, and suggested it had *"remained unmoved, whilst the two continents on opposite sides have crept away in nearly parallel and opposite directions."* In this respect, Taylor's concept was astonishingly modern. Taylor did not make geological reconstructions like his contemporaries Howard Baker or Alfred Wegener, an omission that has reduced his recognition today. Yet Taylor opened a door: In 1915 the first edition of Alfred Wegener's now classic book *The Origin of Continents and Oceans* saw publication. Wegener also recognized the importance of rifting; of the Afar Triangle he wrote: *"If one cuts this triangle out, the opposite corner of Arabia fits perfectly into the gap. As for the mechanics of these rift valleys, they represent an early stage in a complete separation of the two block portions; it may be a question of recent, still* *incomplete rifting or else of an earlier attempt at rifting which died out because of reduction in the strength of the rift forces."*

Wegener rested his hypothesis upon the bedrock of geology, but it was largely the solid Earth that engendered his doom. Although Arthur Holmes argued cogently for a mantle that contained convection cells, dissipated radiogenic heat, and moved the crust at the surface, seismic data of the time suggested the mantle possessed significant strength. What Holmes offered was a physically plausible mechanism by which to drag continents through a deforming mantle, permitting the opening of the Atlantic Ocean by continental drift. However, his insight was not accepted by many prominent geophysicists of the time.

If it was the mantle that doomed the early drifters, it was also the mantle that brought them out of perdition. A product of pure seismology, the confirmation of the existence of the aesthenosphere in 1960 provided mobilists with a rapidly deformable medium through which their continents could serenely glide. They picked up their pace: by 1962 both Harry Hess and Robert Dietz had arrived at the conclusion that the lithosphere was moving like a giant conveyor belt atop the aesthenosphere, and in 1963 Fred Vine and Drummond Matthews published a paper in *NATURE* documenting just such an effect. Today, the Vine Matthews Morely hypothesis (Lawrence Morley, a Canadian geologist, had attempted several times to publish a similar paper) is firmly ensconced in the plate tectonic paradigm.

In an era of ruthless efficiency, it seems almost quaint to ponder this chain of events. But there are deep and meaningful reasons why we should. As in the early 1960s, when the geosciences were altered forever, we are on the cusp of great advances in the understanding of our planet. In this symposium, we are honouring the accomplishments of an Earth scientist who took his stance upon the shoulders of giants, and who, in his own turn, has supported the careers of many others: in twenty-five years, Trond Helge Torsvik has only once published alone.

What a vast and dynamic planet we inhabit! There is no end to what we will discover ~ and it is in the process of discovery that we rattle the links that connect us to our predecessors and mentors. One way or another, each of us owes a debt to Trond Torsvik, and by extension to all those who came before.

TFR, SJHB, MAS
Trondheim, 2007

2 INTRODUCTIONS

2.1 From the Director's Corner -- Everything about the Earth: Science, Sense and Sensibility

Moving continents is not a trivial task. And yet, some people have devoted their life to this very challenging and presumably everlasting mission. When the idea that continents could plough through the crust of ocean basins was introduced by Alfred Wegener 92 years ago, we resisted. Most people are natural born anti-mobilists, and even through we could recognize the South-America – Africa puzzle fit, why should we believe that the Earth's surface has changed through time, and that continents now separated may have been joined together at one point in the past?

A second World War passed, and when we awoke, we were faced with evidence that the magnetic north pole seemingly wandered all over the globe, and that earthquakes, volcanoes, and other active geologic features for the most part are aligned along distinct belts around the world -- belts that define the edges of tectonic plates. In addition, paleomagnetic studies revealed patterns of magnetic reversals in the crust of the ocean basins. Could one really believe that? Today ~ thanks to the new satellite- and GPS technologies that allow us to measure actual plate movements, thanks to the geophysicists and geologists providing us with a growing amount of ground-truth measurements, thanks to modellers testing the hypotheses and bringing them into acceptable explanations ~ today, we do. Thanks to vast legions of highly skilled scientists, including especially Trond Helge Torsvik, who are dedicated to solve the same giant puzzle concerning "everything about the Earth."

In the 1960s the seeds that were sown by Alfred Wegener broke the surface as the earth sciences underwent the plate tectonic revolution. Today, we are experiencing a "fourth-revolution," the development of mantle dynamics. From the newly published (2007) textbook "Terra Mater," to be used by 2nd year high-school students in Norway, we can learn from Trond Torsvik (NGU Annual report 2006): "During the last years the Geological Survey of Norway has built a strong scientific group in Geodynamics. … By combining several disciplines NGU is working on developing a completely new model of Earth dynamic theory, where all the element of plate tectonics are brought steps forward. … The keyword is mantle dynamics … With the mantle dynamics the plate tectonics are brought into something bigger; modelling of flows in the Earth mantle, in seismic images and in the history of the plate movements. …It is just like this, in the collision zone between new and old theories and hypothesis, that science moves forward and that our knowledge about the Earth increases."

This makes sense! Many thanks are due to the author who chose to include this in his textbook, but first of all we should thank Trond and the Geodynamics team at NGU for presenting this statement to our next generation and for having the ambitions and skills to follow this goal.

Morten Smelror
Administrative Director
Geological Survey of Norway
Trondheim, 2007

2.2 Trond H. Torsvik, NGU and Statoil – A far reaching journey

The Statoil cooperation with Professor Trond H. Torsvik and his co-workers at NGU in Trondheim reminds us about a journey into the unknown. When this journey started, we were not sure what we might see or how long it would take. We can be sure about one thing however, without Trond this journey would not have started.

It's not easy to define exactly when this special journey started, but for simplicity we will begin our story with the initiation of the "BAT" project in 1998. BAT became the acronym for a huge consortium project titled "Basin Analysis and Applied Thermochronology on the Mid-Norwegian Shelf". The project was sponsored by most of the oil companies active on the Norwegian Shelf at that time. Trond's impact on this project gradually increased during its five year lifespan, and he played a major role in producing one of the key end products of the project: "BATLAS – Mid Norway plate reconstruction atlas with global and Atlantic perspectives".

In 2000 Trond Torsvik was appointed a VISTA Professor. VISTA is a research cooperation between The Norwegian Academy of Science and Statoil, which funds research fellowships within the Norwegian research communities. This was another chance for Statoil to get a first hand insight into Trond's scientific work and to realize its potential impact on petroleum exploration. At the end of the BAT project in 2002, Trond and his scientific co-workers around the world proposed to the oil industry to sponsor the development of GPlates - a new software tool for integrated plate tectonic and geodynamic modelling. Only Statoil took up the offer. By now the speed of our journey was picking up.

Having made a good start in the North Atlantic, Statoil proposed to continue the journey and make the South Atlantic the next stop. Trond and his steadily increasing group of scientists within the Geodynamics team at NGU took up the challenge and delivered some excellent products that are still being used internally in Statoil. NGU kept up the momentum of the journey and proposed a three years research project with the stunning name: "Frontier Science and Exploration: the Atlantic – Arctic". Not only did it cover approximately half of the globe, but it also offered to take us to a place where no other oil company had been – the deep mantle. We went along with it, and the next stop of the journey was the Arctic. The last couple of years different teams at NGU together with co-workers internationally have done a lot of excellent research on regional tectonic evolution of the High Arctic. Statoil has been supporting most of these projects, and we are now seeing a series of outstanding products coming out of these projects. In addition, Trond and his co-workers have developed the SPlates software for internal use in NGU and Statoil. SPlates is highly sophisticated software for plate tectonic and geodynamic modelling. It is now being actively used for in-house exploration projects in Statoil (See abstracts by Bjørnseth et al. and Ball et al. in this volume).

Finally, we would like to say congratulations Trond! We have been on a long journey together, but it's not over yet. There is so much more to see, learn, wonder about, discuss and synthesise. We think it's an important journey that Statoil should take part in. Let's keep on moving!

Hans Morten Bjørnseth, Bruce Tocher and Philip Ball
Statoil ASA
Stavanger, 2007

2.3 An academic view: PGP celebrates Trond's 50th anniversary and his contributions to the fields of geodynamics, geomagnetism and paleogeography.

Trond H. Torsvik is clearly one of the most innovative and excellent geo-scientists in Norway. PGP therefore applauds this opportunity to celebrate his 50-year anniversary. Trond is a world-leading scientist in his field of research. He has contributed not only to basic scientific knowledge by collecting and analysing astonishing amounts of data from many parts of the world, but also in producing useful tools required to analyse large amounts of data such as the IAPD and GMAP programs. Recently, we have been impressed by the compilation and creative analyses of data from hotpots and large igneous provinces (LIPS). Much of Trond's work has been dedicated to paleogeographic reconstructions that were initially used to explain the tectonic evolution of the Caledonides, particularly of the North Atlantic Region. The "Baltica up side down" along with an amazing number of papers from the Oxford period, which may be referred to as "the Hollybush papers" are classic in this respect. The paleogeographic reconstructions led to an almost worldwide activity, addressing problems such as super-volcanoes, super-continents, the snowball earth hypothesis, non-dipole fields, and LIPS. Like many strong personalities before him, Trond spent long periods in remote parts of Siberia. We consider Trond's current work on LIPS extremely exciting and it may contribute to a breakthrough in the, otherwise missing, causal links that couple surface plate-motions and mantle dynamics.

Trond's departure from the Norwegian Naval Academy and the subsequent start of his academic career at the University of Bergen in the late 1970's can perhaps be regarded as a win-win situation for the World in general and for Science in particular. As "evil empires" and "axes of evil" are homing in on us, it becomes a scary thought to reflect on what Trond could have achieved on the high seas as an Admiral (he would of course have become one). We could easily have entered into battle with both enemies and friends, and perhaps even won? It is definitely better, although at times still painful to have him fight battles in Science, even if this also occasionally has produced some casualties.

Today Trond is a part-time PGP'an. This is our second marriage. After a brief marriage no.1, followed by Trond's self-proclaimed war and widely broadcasted divorce from us, we had a more or less Trond-free period, although some PGP'ans continued to work and publish with him "under-cover." We entered a generally peaceful period only interrupted by the occasional domestic disagreement that any high-energy science environment will experience from time to time. Our lives got back on the track and PGP became a success story as did Trond's geodynamics group in Trondheim.

Then, like an old lover that you had almost, but not quiet forgotten, Trond approached us again. Initially fuelled by the grape-wine, however, chats about the good old days when everybody was younger, fitter and drank more, and were soon overtaken by more serious discussion of current science. Eventually, Admiral Torsvik from Terra Omnis was ready to propose again. This is his gift: when he makes a proposal, he is so hard to turn down. At PGP we all firmly believe that as long as his sails are up, Trond will be faithful to science and entertaining to mankind. So, after a deep breath we let him come close again. We admit that we are happy about this. It feels right and natural to be here and contribute to this grand seminar to honour his life and research.

PGP looks forward to getting older and wiser along with you. We are certain that Science will benefit from our second marriage. Skål to Admiral Torsvik, one of the greatest geo-lovers that was ever raised.

Torgeir Andersen, Bjørn Jamtveit
Physics of Geological Processes
University of Oslo
Oslo, 2007

2.4 Echos from the past: On the importance of (royal) stags

It is an honour for me to give this address at Tronds 50 year celebration. Everybody here knows Trond both as a scientist and a friend and so I will not make a presentation of Professor Trond Torsvik. Instead of talking about Trond Torsvik, I will talk about stags ~ royal stags, or in Norwegian, kronhjort. The Norwegian word kron (or in English, crown) is referring to the beautiful horns. The deer live in groups or herds with internal rules and hierarchy.

A science organisation has many similarities with a group of deer, an orchestra, a theatre or a soccer team. They are all based on a combination of individual talent and team work. The scientist must be talented before entering the organisation. Team work, however, may in some cases, be developed within the organisation. The selection of talented scientists is therefore the most important task for the leaders in an organisation. To develop your post docs into good scientists you need a challenging scientific environment, and that is why you need kronhjorter.

A kronhjort is a female or a male scientist that is easily recognised as the best and most influential in a group based on their scientific horns. The kronhjort may also have a formal position as group leader. Kronhjortene are setting a scientific standard in an organisation, which young scientists are trying to reach. The royal stags also play an important role in making the organisation known both nationally and internationally.

In a herd of deer, the stag is usually friendly with all the deer. There is, however, one exception. If challenged by a younger stag the kronhjort usually confronts the stag immediately. There must be no doubt about who is the kronhjort,

Based on the authority (horns) the kronhjorts have a strong influence in every organisation. This authority can, in a few cases be used to strengthen the progress planned by the leaders or (which is the case for most scientific organisations), be used against proposals from directors. To ignore the kronhjorts may work for a short time; in the long run, however, it may turn out to be a bad choice. It is unbelievable how much creativity a scientist can use in the fight against authorities. It takes around ten years to build a high quality group and it takes less than a year to destroy it.

Royal stags want to be treated differently than other scientists. They expect to be visited by the director and have a direct access to the director's office. This informal contact is often to the benefit of both leaders and stags.

The royal stags may be developed through a fight with other stags within a herd or imported from other herds. The royal stags that have been through the internal selection process have often an advantage.

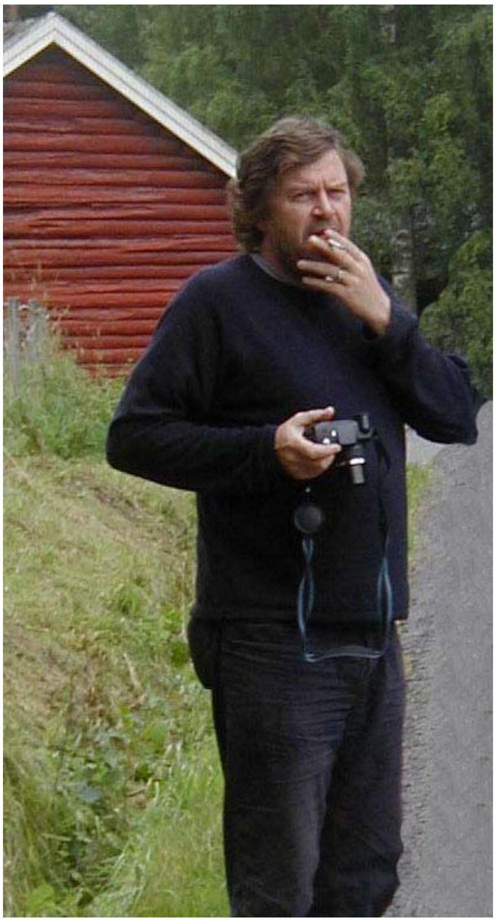
The royal stags are important in herds of deer, soccer teams, orchestras and science organisations. It is an important part of the work of the director to develop high quality royal stags.

All similarities between royal stags and Trond Torsvik are purely accidental.

Arne Bjørlykke
Geological Survey of Norway
Trondheim, 2007

3 TROND HELGE TORSVIK

3.1 A short biographical note



Trond Helge Torsvik was born in a hovel only marginally attached to a steep, rain-soaked mountainside not far from Bergen, Norway. His last name (the gift of his God-fearing, Christian parents) reflects that of a pagan, not-so-intelligent minor deity best known for trying to drink the ocean dry under the mistaken impression it was a giant puddle of mead. Expelled from the Norwegian Naval Academy following a series of colourful incidents in the Red Light districts of ports such as Rotterdam, Trond embarked upon a series of marriages that would make any harem master proud. Entering the University of Bergen as an expectant father, Trond began managing an illegal nightclub in order to make ends meet. Faced with incipient financial ruin (living up to his name sake, Trond tended to drink up the night's profits before the sun rose), he teamed up with Karsten Storetvedt to save the world and make it safe for Democracy. But fate intervened, spoiling the best-laid plans. Locked out of Bergen's paleomagnetic laboratory, Trond set his sails for Oxford. A veritable flurry of scientific papers followed, spawned by the sheer excitement of the intellectual environment in which Trond now found himself. A few years later Trond joined the Geological Survey of Norway, and the local pub in Oxford promptly went broke. Quitting the Survey the day before he arrived over a difference of opinion best left unspoken, Trond was tracked down in the Copenhagen Tivoli by the Administrative Director who, rendering his prey senseless with a case of Bordeaux, returned to Trondheim in triumph. And there Trond found his home, commuting daily from the wrong side of the tracks to the government institution he would soon help raise from obscurity to international renown. From an office rendered opaque by cigarette smoke Trond founded the Centre of Geodynamics, delving to the Core Mantle Boundary to expose the Earth's innermost secrets. Then, he met his fourth wife-to-be. With one foot firmly planted in the hot, molten iron of the outer core, Trond now rests his other on the heights of Olympus Mons. Spanning the Solar System, Trond enters his second half-century with an interplanetary vision firmly kept in check by fine whiskey, his only vice. *Weritas! Sacrae boves hamburguras optimus fiant!*

4 THE PROGRAMME

4.1 Friday, 21 September, 2007

9:00-9:10: Introductory Remarks and Welcome- **Bruce Tocher,** Statoil ASA
9:10-9:15: Introductory Remarks and Welcome- **Morten Smelror**, NGU
9:15-9:25: Introductory Remarks and Welcome- **Rob Van der Voo**, University of Michigan

(Session Chair: Joe Meert)
9:25-9:50: **Hans Morten Bjornseth**: Regional tectonic analysis in Statoil: Why do we care?
9:50-10:15**: Erik Halvorsen**: Anisotropy of magnetic susceptibility in sills from the diabasodden suite (early Cretaceous), Svalbard with geological implications.

10:15-10:35 Break

10:35-11:00: **Mikhail Bazhenov**: Paleomagnetic constraints on the Kazakhstan-Siberia relationship in the Paleozoic.
11:00-11:25: **Stuart Gilder**: A paleomagnetic paradox from the Tarim basin
11:25-11:50: **Harald Walderhaug**- Late Precambrian paleogeography of Baltica

11:50-12:05 Break

(Session Chair: Mark Smethurst)
12:05-12:30: **Manoj Pandit**- Paleomagnetism and Geochronology of the Malani Igneous Suite, Northwest India: Implications for the configuration of Rodinia and the assembly of Gondwana
12:30-12:55: **Joe Meert**- India's changing place in global Neoproterozoic reconstructions: New Geochronologic constraints on key paleomagnetic poles.

13:00-14:15: LUNCH & POSTERS

14:15-14:40: **Ebbe Hartz**- Force, energy and petrology balanced geodynamics: Rock-number symbiosis or 'sitting between chairs'?
14:40-15:05: **Lew Ashwal**- Can we rely on tectonic discrimination of granitoids using geochemistry? An example from the Seychelles
15:05-15:30: **Sue Webb**- Adventures in the Bushveld, South Africa

15:30-16:10 Break & Posters

(Session Chair: Susanne Buiter)
16:10-16:35: **Rob Van der Voo**: An orocline that may have involved the entire crust.
16:35-17:00**: Peter Robinson*:*** Flavor of earliest Iapetus MORB, with local hot-spot influence, recorded through geochemical tracing of the Neoproterozoic Ottfjället dike swarm of the Middle Allochthon into the Scandian hinterland, Western Gneiss Region, Norway

17:00-17:10 Break

17:10-17:35**: Conall Mac Niocaill:** The Neoproterozoic Glacial World: East Greenland revisited

17:35-18:00: **Torgeir Andersen**: An outrageous THT statement and how it contributed to the understanding of the Caledonides

19:30: Informal Dinner in Trondheim at Zia Teresa

4.2 Saturday, 22 September, 2007

9:30- 9:45: Introductory Remarks and Welcome- **Joe Meert**, University of Florida

(Session Chair: Rob Van der Voo)
9:45-10:10: **Judy Hannah**- 560 Ma and 300 Ma Re-Os ages constrain Neoproterozoic glaciation and record Variscan hydrocarbon migration on extension in the Oslo Rift.
10:10-10:35: **Fernando Corfu**- Perplexing Novaya Zemlya: The mystery of 700 Ma mafic dikes cutting Devonian strata

10:35-10:50 Break

10:50-11:15: **Sergei Medvedev**- Stressing, bending and stretching Trond's (g)plates.
11:15-11:40:**Yuri Podladchikov**- Some thoughts on the immovability of the Trond anomaly.

11:40-11:55 Break

(Session Chair: Conall Mac Niocaill)
11:55-12:20: **Phillip Ball**- Plate tectonic modeling and retro-deformation of passive margins using regional structural constraints: The evolution of the Jan Mayen microcontinent and the Norwegian-Greenland sea.
12:20-12:45: **O. Olesen**: Aeromagnetic remapping of the Norwegian Sea

12:45-14:15: LUNCH & POSTERS

14:15-14:40: **Paul Ryan**- New granites heal old sutures.
14:40-15:05: **Mike Gurnis**- Assimilation of plate tectonic reconstructions into regional and global models of mantle convection.
15:05-15:30: **Dave Yuen**- Interactive visualization and monitoring of 3-D mantle convection

15:30-15:50: Break

15:50-16:15: **Tim Redfield**: Escape Tectonics and the extrusion of Alaska: Past, Present and Future
16:15-16:40: **Kevin Burke**- Plate Tectonics: The Gift that goes on Giving.

16:40-18:45: Discussion, Posters and Social Time
18:45: Bus Transportation to Ringve Museum Banquet
19:00: Dinner and Roast of Trond Torsvik at Ringve Museum- Lade

4.3 List of Posters

1. Bernard Bingen et al. - Crustal Architecture of the Mozambique Belt in northeastern Mozambique: Perspective from U-PB geochronology and LU-HF isotopes in zircon

2. Susanne Buiter and Trond Torsvik- Horizontal movements in the eastern Barents Sea constrained by numerical models and plate reconstructions

3. Carmen Gaina and CAMP-GM group - Circum-Arctic Mapping Project: New magnetic and gravity anomaly maps of the Arctic

4. M. Ganerød, S. Rousse, M. Smethurst and T Prestvik - Constraining the history of the North Atlantic Igneous Province: new constraints from the Isle of Mull, Scotland.

5. Laurent Gernigon et al. - Syn-and post-breakup magmato-tectonic evolution of the mid-Norwegian volcanic rifted margin

6. Laura Gregory et al. - Paleomagnetic studies on mafic dykes and U – Pb age data on rhoylitic tuff in the Malani Igneous Suite, NW India: Implications for the configuration of Rodinia

7. Antje Kellner- Different styles of deformation of the fore-arc wedge along the Chilean convergent margin: Insights from 3-D numerical experiments.

8. Cinthia Labails and GM-LGG Ifremer - Observations about continental crustal thinning inferred from Reflection and Refraction Seismic Data Analysis on Central Atlantic margins

9. Karen Mair, Steffen Abe and Torbjørn Bjørk - Breaking up: Fault gouge evolution during shear

10. R.D. Müller, C. Gaina, M. Sdrolias and T. Torsvik- Farallon-Izanagi-Alaska plate motions, trench and ridge subduction offshore Alaska during the Cretaceous

11. C. Pascal, D. Roberts, R.H. Gabrielsen and O. Olesen - Present-day stress orientations in Norway as deduced from stress-release features and active, post-glacial reverse faulting

12. Sonia Rousse, Morgan Ganerød, Mark Smethurst and Trond Torsvik - Multiple antipodal remanence components in the Skye lava (UK): Complex thermal and chemical history and self-reversals

13. Bernhard Steinberger and Trond H. Torsvik - TPW unplugged: Absolute plate motions and true polar wander in the absence of hotspot tracks

14. Trond H. Torsvik, Mark A. Smethurst, Kevin Burke and Bernhard Steinberger - Large igneous provinces generated from the margins of the large low-velocity provinces in the deep mantle

5 THE ABSTRACTS

5.1 An outrageous THT statement and how it contributed to the understanding of the Caledonides

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20 years ago THT worked intensively with co-workers and mentors [one present and one looking down or up (?) at us with pride], to produce paleogeographic reconstructions, quantify plate-motions and to test previous statements of large sinistral strike-slip movements during later stages of the Caledonian orogeny and after. Paleomagnetism of the Old-Red sandstone basins of Norway was shown to be mostly reset, with several magnetizations spanning the mid-Palaeozoic to Mesozoic. Magnetic fabrics and unfolding analyses showed coincidence of magnetic anisotropy with structures in the field and backed up the paleomagnetism showing resetting. Contemporaneous work in and around the basins by several others showed that very thick zones (up to 5 km) of mylonites occurred in the substrate of several of the basins. Many of us had learned to use kinematic indicators (pioneered mostly by French geologists in the late 1970-ies) as a tool to interpret kinematics of high-strain zones. Our mylonites showed top-to-west displacement, opposite to the Caledonian thrust direction. We had also read about metamorphic core-complexes and extensional detachments in the Basin and Range province of the western US. Those of us who worked on the mylonites separating eclogites of late Silurian to early Devonian age (400-420 Ma) became convinced that it was necessary to see the exhumation of eclogites, formation of the mylonites and overlying Devonian basins as a continuous process with causal links.

Then lightning struck; we could read as the final statement in the abstract of the paper: *The tectono-magnetic signature of the Old Red Sandstone and pre-Devonian strata in the Håsteinen area, Western Norway, and implications for the later stages of the Caledonian Orogeny. Tectonics, 6, 3, 305-322,* by THT et al.: that: “Some recent extensional-basin models appealing to listric normal faulting to account for both the sedimentation and subsequent deformation of the Western Norwegian Devonian Rocks, are rejected on the basis of inadequate structural information.”

Inadequate structural information? How was it possible that Trond and his presumably sensible co-workers could write this, and get it published in a journal where J F. Dewey was the senior editor? We could not let this ‘outrageous’ statement be the final word. Trond was called in and we arranged a fieldtrip for the chosen few, (including JFD) to find out what we agreed about and not. A week in the field sorted out most problems, and after the very late final night of our field seminar in Florø, Trond thought it was time to change his career to become lawyer. Fortunately, he had forgotten this by next morning. The provocative paper(s) and the field trip eventually resulted in a research effort with several group (US, UK, France, Norway). 20 years later West-Norway is a world famous type-area for extensional tectonics, extensional-supra-detachment basin formation and exhumation of HP-UHP rocks! This is documented by more than 20 PhDs and somewhere between 50 and 100 papers. This talk will present some of examples of why the region now is a type-area and what we have learned since 1987.

5.2 Can we rely on tectonic discrimination of granitoids using geochemistry? An example from the Seychelles

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Constraining tectonic setting in old rocks is one goal of geoscience. Comparison of various features with well known modern examples is the most fruitful approach, although the sole use of geochemistry as a tectonic discriminator does not always work well. A good example is the unmetamorphosed Neoproterozoic granitoids of the Seychelles, which have been interpreted by almost all workers as having formed in an extensional, hotspot- or rift-related tectonic setting. The main evidence includes their perceived alkaline character, their depletions in $\delta^{18}O$ and trace element signatures that plot in the "within-plate" field. Our group has acquired an extensive database of WR geochemistry, Sr-Nd-O isotopes, U-Pb zircon ages and paleomagnetic determinations, which are better interpreted in terms of a continental or Andean-type arc setting [1-4]. Arguments are as follows: Lithologies include subsolvus and hypersolvus granodiorites and monzogabbros, with coeval dolerite dykes, resulting in a variety of intermediate rocks occurring as enclaves and irregular masses [1]; this assemblage is common in Andean plutons. Ages span ~100 m.y. (703-809 Ma, mainly 752 ± 4 Ma), difficult to reconcile with plume- or rift-related models [2]. Two groups of granitoids can be distinguished, whose petrology, geochemistry and isotopic compositions (εNd 750 = +2.85 to -3.83; ISr = 0.7031– 0.7263) imply derivation from variable proportions of a mixed source composed of a juvenile, mantle-derived component, and an ancient component similar to Archean tonalitic gneisses in NW India [1]. We argue that the low $\delta^{18}O$ (4.1 ± 2.6 $^{o}/_{oo}$) of Seychelles granitoids relative to most igneous rocks (5.5-11 $^{o}/_{oo}$) is a source feature, rather than implying surface water interaction with extensional magma chambers [3]. Paleomagnetic data constrain the position of the Seychelles to the margins of a then extant (super)continent at ~750 Ma, consistent with a continental arc setting [4]. Reliance on geochemical discrimination alone, therefore, could result in a misleading inference regarding the tectonic setting of Seychelles, and other granitoids.

References

[1] Ashwal L.D., Demaiffe D. and Torsvik, T.H. 2002. J Petrol 43, 45-83.
[2] Tucker R.D., Ashwal, L.D. and Torsvik, T.H. 2001. EPSL 187, 27-38.
[3] Harris C. and Ashwal L.D. 2002. CMP 143, 366-376.
[4] Torsvik T.H., Ashwal L.D., Tucker R.D. and Eide E.A. 2001. Precamb Res 110, 47-59.

5.3 Plate tectonic modelling and retro-deformation of passive margins using regional structural constraints: The Evolution of the Jan Mayen microcontinent and the Norwegian-Greenland Sea.

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We have revisited the evolution of the NE Atlantic domain since the Jurassic by integrating a wealth of data (regional gravity, magnetic, bathymetric and seismic reflection) into a quantitative plate reconstruction. The integrated plate model utilises revised interpretations of the continent-ocean transition, structural observations from new 2-D seismic data covering the Jan Mayen microcontinent and the Møre and Vøring Basins, and regional structural and geological observations from the conjugate Norwegian and Greenland margins. Classical models treat Greenland and Eurasia as rigid plates with plate boundaries that changed little since the breakup. This study represents a first attempt to retro-deform plate boundaries. The model was created utilising a semi-rigid plate model to create a set of reconstructions and palaeogeographies back to a pre-Jurassic rift 175 Ma configuration. The underlying assumption was that overlaps within the plate model could be explained using a heterogeneous deformation model. The resulting plate models and structural observations have been used to suggest a new tectonic model for the Jan Mayen microcontinent.

5.4 New paleomagnetic data from the Chingiz Range: a through-Paleozoic connection between East Kazakhstan and Siberia?

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Tectonic evolution of the Ural-Mongol belt between Baltica, Siberia, and Tarim is a key to formation of the Eurasian supercontinent during Paleozoic time, but the views on this enigmatic process still remain very controversial. We carried out a paleomagnetic study of mid-Silurian, Lower-lower Middle Devonian and Middle Devonian volcanics at three localities along the southwestern boundary of the Chingiz Range (NE Kazakhstan). A single-polarity characteristic component in mid-Silurian andesites is likely to be primary by judging a positive test on intraformational conglomerates. Both reverse postfolding and dual-polarity prefolding components are isolated from two Devonian collections. These new data are combined with published results on Upper Cambrian to Upper Permian rocks from the Chingiz Range, and the polarity of each result is established. We conclude that the study area was steadily, albeit with variable velocity, moving from intermediate southern to intermediate northern latitudes during the Paleozoic. New Middle Paleozoic paleomagnetic data from the Chingiz range also reinforce the hypothesis that the strongly curved volcanic belts of Kazakhstan are of oroclinal origin. We compared the Chingiz data with the Siberian reference ones and found that the paleolatitudes of these two units well agree, if the Siberian apparent polar wander path is seriously revised. We discuss possible implications, which coherent motion of the Chingiz unit and Siberia during most Paleozoic imposes on the paleogeography of the Ural-Mongol belt.

5.5 Crustal Architecture of the Mozambique Belt in northeastern Mozambique: Perspective from U-PB geochronology and LU-HF isotopes in zircon

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Reconnaissance geological mapping was performed at 1:250000 scale over 31 degree-square sheets in NE Mozambique (Norconsult Consortium 2007), supported by airborne magnetic and radiometric surveys, U-Pb geochronology of zircon and monazite by LA-ICPMS and SIMS in 80 samples, and Lu-Hf isotope data on zircon by LA-MC-ICPMS in 32 samples. The study has led to a new tectonostratigraphic model of the area and to improved understanding of the relationships between the Mozambique, Zambezi, Irumide and Dronning Maud Land belts.

The area hosts the WSW-ENE trending, NNW-dipping, Lurio belt, a major linear Pan-African structure which gradually disappears westwards, and contains 557 ±16 Ma high-P granulite boudins, evidence for deformation between 587±23 and at least 532±13 Ma and abundant 612±6 to 504±11 Ma felsic plutons.

NW of the Karoo-aged Maniamba graben, the Palaeoproterozoic Ponta Messuli Complex preserves a low-P 1950±15 Ma metamorphism and was intruded by 1056±11 Ma granite, with an Archaean Hf model age (εHf = -15). This complex is related to the Irumide and Usagaran belts at the margin of the Congo-Tanzania craton. It is overlain by the Txitonga Group, which contains 714±17 Ma felsic volcanics with εHf = -6, and is interpreted as a Neoproterozoic rift sequence deposited along this margin. SW of the Maniamba graben, the Meso- to Neoproterozoic Unango and Marrupa Complexes consist of 1062±13 to 949±13 Ma felsic orthogneiss with Palaeo- to Mesoproterozoic Hf model ages (-11 < εHf < +7). They show 962±18 Ma Grenvillian metamorphism (granulite-facies in Unango), 799±8 Ma alkaline plutons, 551±6 to 536±6 Ma Pan-African metamorphism, 547±14 to 486±27 Ma granite plutons, and SW-NE trending 444 ±5 Ma ultramylonites close to the Maniamba graben. The two Complexes can be interpreted as an extension of the southern Irumide belt, linking the Zambezi and Mozambique belts.

The Marrupa Complex is overlain by a Pan-African Upper Nappe System (UNS) including, from NW to SE, the M'Sawize, Muaquia, Xixano, Lalamo, Meluco and Montepuez Complexes. It consists of Neoproterozoic metasedimentary rocks, including marble, and comparatively juvenile magmatic suites, including 973±11 to 946±12 Ma mafic to felsic orthogneiss (M'Sawize, Muaquia, Meluco, εHf = +2), 818±10 to 787±23 Ma metarhyolitegranite (Xixano, Montepuez), 744±11 to 735±4 Ma enderbite and granite (Xixano, +4 < εHf < +10), 696±13 Ma granodioritic gneiss (Lalamo, εHf = +10), and 631±11 to 579±27 Ma felsic plutons. The Upper Nappe System preserves two metamorphic phases at 735±4 Ma (granulite-facies, Xixano) and 631±6 to 607±11 Ma (M'Sawize, Xixano, Meluco). It correlates well with the Western Granulite nappes of Tanzania. The Upper Nappe System is interpreted as remnants of an early Pan-African collision zone (631–607 Ma), involving indigenous and accreted lithologies, and transported with top-to-NW kinematics onto the Congo-Tanzania margin between 596±11 Ma (youngest pluton in the nappes) and ca. 550 Ma (metamorphism in underlying Marrupa Complex). A large 744–735 Ma enderbite body in the Xixano Complex is regarded as the root of an accreted arc formed in the Mozambique ocean.

S of the Lurio belt, the Nampula Complex consists mainly of 1148±1 to 1028±7 Ma felsic orthogneiss (+1 < εHf < +4), on average older and more juvenile than equivalent lithologies N of the Lurio belt. It is affected by 543±23 and 520±8 to 493±8 Ma metamorphism and hosts abundant 511±12 to 508±3 Ma granite plutons. It is covered by the clastic Mecuburi Group, and overlain by the Mugeba and Monapo klippen, possibly part of the Upper Nappe System. The Nampula Complex shows late Pan-African unroofing (post 493 Ma) and has clear affinity with the Dronning Maud Land belt. The status of the Lurio belt, as a Grenvillian or Pan-African suture zone, or none of the two, remains a matter of debate.

References

Norconsult Consortium, 2007. Mineral resources management capacity building project, Republic of Mozambique, Component 2: Geological infrastructure development project, Geological Mapping Lot 1, Report No. B6.f. Unpublished, 778 pp.

5.6 Regional tectonic analysis in Statoil – Why do we care?

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Statoil has the last few years invested a lot of time and money on internal and external research projects aimed at developing new tools and workflows for regional tectonic analysis. The rationale for this is of course that we do believe it will help us finding more oil and gas. The key objective is to improve our predictions of reservoir rocks, source rocks, seals, traps and heat-flow in space and time. The quality of such predictions is essential for any exploration campaign. The links between these elements and regional tectonic analysis are particularly important in regions with limited previous exploration. Incorporation of regional tectonic analyses in petroleum exploration workflows optimized for such regions is illustrated by the three examples below.

The first example is taken from the Columbus Basin, located east of Venezuela and southeast of Trinidad. At a first glance, the Columbus Basin looks like a typical Atlantic passive margin basin, dominated by the huge sediment supply from the Orinoco River. However, a regional tectonic analysis very quickly revealed that its Late Cenozoic history is strongly affected by the active subduction zone to the north. This effect became important in Miocene time, and must be taken into account when predicting the regional distribution of reservoir rocks, seals and traps in the Columbus Basin. The key source rock in the region is of Late Cretaceous age. During that time the Columbus Basin was a passive margin. Mapping the crustal architecture and reconstructing the tectonic evolution of this older margin is important for a regional understanding of this Late Cretaceous petroleum system.

The second example is a combined plate reconstruction and tectonic analysis of the Norwegian – Greenland Sea. This study integrated geophysical datasets, structural observations and models to develop new palaeogeographic maps of the Norwegian-Greenland Sea. In addition the interpretation of structural data from the conjugate margins and the Jan Mayen region has resulted in a new tectonic model for the Jan Mayen microcontinent. The SPlates software developed by Trond Torsvik and his team at NGU was an essential tool for this in-house study.

The third example is an integrated gravity, magnetic and tectonic modelling study from the Eastern Barents Sea. A large elongated basin, trending roughly parallel to Novaya Zemlya is located in the central part of the Eastern Barents Sea. The structural style and the very large wavelength of this basin indicate that it is probably not a foreland basin. The sediment thickness is up to 20 km, yet the Moho appears to be almost flat. The major normal faults that are typical of rifts have not been observed. Subsidence analyses revealed an accelerated subsidence event in Late Permian to Early Triassic times. This event can not be explained by traditional rift models alone. Based on this in-house modelling, Statoil has initiated several external research projects to improve our understanding of the enigmatic tectonic history of the Eastern Barents Sea.

5.7 Horizontal movements in the eastern Barents Sea constrained by numerical models and plate reconstructions

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The eastern Barents Sea basins, west of Novaya Zemlya, are characterised by a large width (over 400 km) and a substantial thickness of the basin sediments of more than 10 km on average. Mild folds in the basin sediments and large thrusts at the eastern basin margin indicate that the region underwent shortening at a time between the Late Permian and Early Jurassic. It is assumed that the crustal part of Novaya Zemlya was thrust westward, but the magnitude of this compressive movement is not well known. Our aim is to provide an order-of-magnitude constraint on the amount of shortening associated with the displacement of Novaya Zemlya and the inversion of the eastern Barents Sea basins by combining numerical models and plate reconstructions in an iterative process.

We use a 2D thermo-mechanical finite-element method to model inversion of a predefined basin. The total amount of shortening imposed on the models is first constrained by plate reconstructions for the Barents Sea region for the late Palaeozoic to early Mesozoic. The magnitude of the westward movement of Novaya Zemlya in these reconstructions is, however, highly uncertain due to the allochthonous nature of the rocks of the island and the scarcity of palaeomagnetic data in the region. Our models show that shortening localises in the model basin and at Novaya Zemlya and that westward propagation of deformation is more efficient when the strength of the lower crust is reduced. By comparing the inversion obtained in the numerical models to the inferred inversion structures in the eastern Barents Sea basin we further constrain the amount of shortening that caused the inversion and therewith improve the plate reconstructions for the region. Our models indicate that the westward movement of Novaya Zemlya occurred in the Late Triassic-Early Jurassic (220-190 Ma) and was limited in magnitude to 100-200 km, which is considerably less than previous estimates (500-700 km)

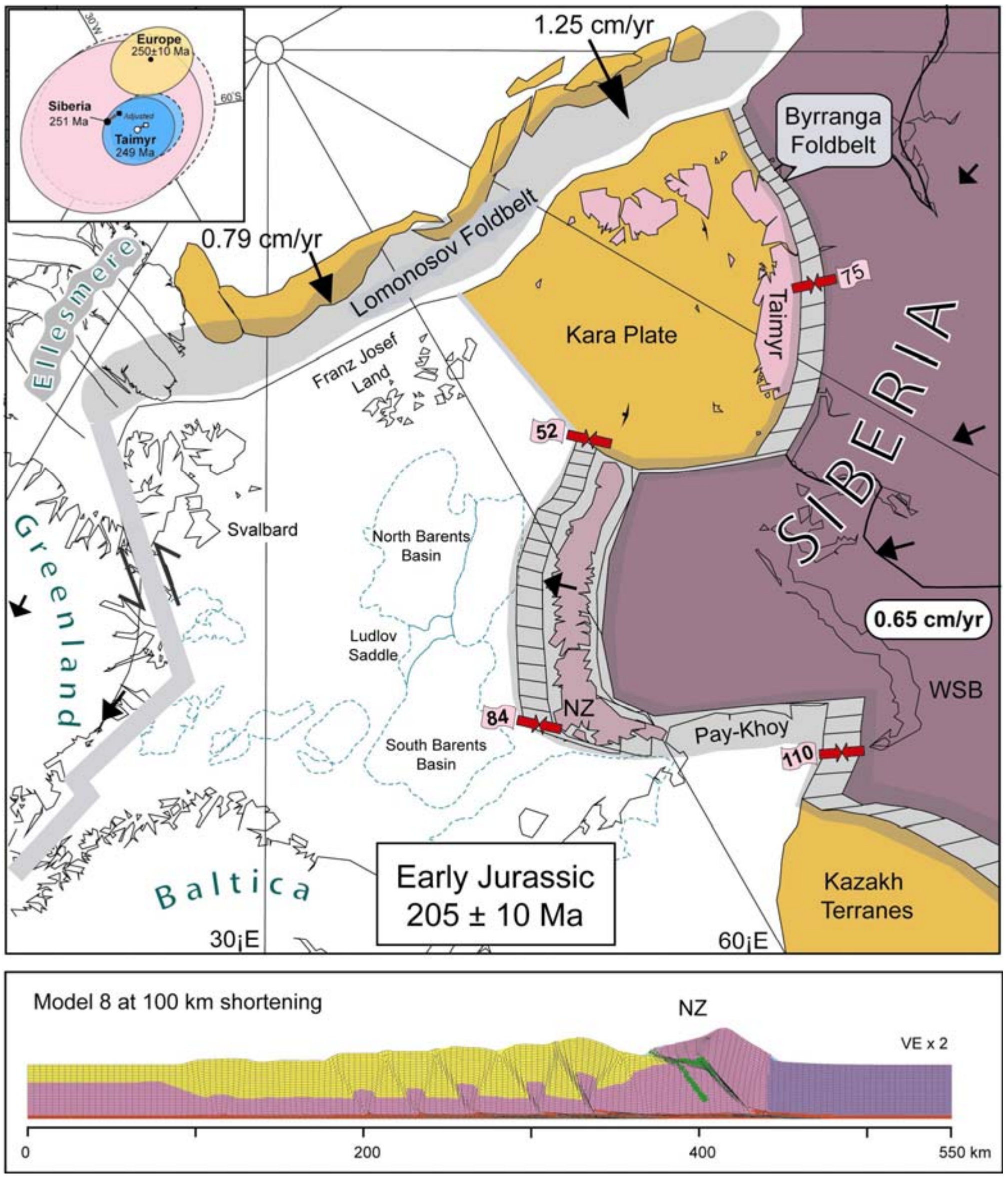

Figure: Plate reconstruction at ca. 205 Ma in which Baltica, with the Barents Sea, is kept fixed. The reconstruction is halfway through the Late Triassic-Early Jurassic compressional event (Byrranga foldbelt) and the Siberian plate has been pushed with around 100 km. The grey-shaded areas denote areas that are affected by this deformation and the striped areas denote the subsequent difference between 205 and 190 Ma. The compressional arrows denote the stress-field direction, the numbers in the pink boxes represent the amount of subsequent compression (in km) that will occur and the single black arrows are point velocities At the same time as the Byrranga fold and thrust belt is developed we anticipate that Lomonosov terranes are colliding along the north Barents Sea margin, while the West Barents Sea margin is undergoing large-scale strike faulting. The lower diagram shows one of our models after 100 km of shortening. Pre-existing thrusts facilitate thrusting of Novaya Zemlya material over the eastern margin of the Barents Sea, while simultaneously thrusts develop in the Barents Sea basin. Top-left inset compares the ca. 250 Ma mean palaeomagnetic poles from Europe, Siberia and Taimyr. The mean poles are plotted with 95% confidence ovals. Our plate tectonic reconstruction improves the correlation between Europe, Siberia and Taimyr. However, both the adjusted and the in-situ pole for Siberia plot within the 95% confidence oval of Europe. The Taimyr in-situ pole differs from the European one, but only around 100 km of convergence is needed to make the Taimyr and European pole overlap within their 95% confidence oval. Base on these data, we, therefore, estimate that the displacement of the Siberian plate was 100 km at a minimum, but the upper estimate from the palaeo-magnetic data exceeds 1000 kilometres.

5.8 Plate tectonics: The gift that goes on giving

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Plate tectonics, the rotation of rigid objects across the Earth's Surface, is the gift that goes on giving. The better the understanding of the operation of that basically simple process as it applies to the complex Earth System the better becomes the general understanding of how the system works.

Trond's contributions to the understanding of the Earth system are well known so I focus only on some of his most recent work that I consider to be particularly significant viz the demonstration, by rigid body rotation, that the plumes which generated the Large Igneous Provinces of the past 300 My rose rapidly from the margins of Low Shear Wave Velocity Provinces at the CMB (Torsvik et al. G.J.Intl. 2006). That finding greatly changes understanding of mantle tomography, mantle dynamics and the 300 My history of the geoid. Extrapolated to as far back as 2.5 to 4.5 Ga the finding throws new light on: the geochemical evolution of the silicate Earth, the long-term stability of deep mantle structure, the thermal history of the core and the large-scale structure of the planet Mars.

What might Trond do next?

5.9 Perplexing Novaya Zemlya: the mystery of 700 Ma mafic intrusives cutting Devonian strata

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A scientific expedition led by Olaf Holtedahl to Novaya Zemlya in 1921 brought back abundant scientific information and samples (Nakrem and Gradstein 2007). Later in the century some sectors of the islands were turned into nuclear testing grounds, rendering them next to inaccessible for geological field work. Because of this, the Holdedahl sample collection has become increasingly more valuable.

Our interest in samples of the Holtedahl collection stems from the work on the role played by large-scale mafic magmatic systems, which intrude sedimentary basins such a the North Atlantic or Karroo, and affect the climate by causing the release of significant quantities of greenhouse gases (e.g. Svensen et al. 2004). The report of mafic sills and dykes of likely Mesozoic age cutting fossiliferous Devonian strata in south-central Novaya Zemlya provided an opportunity to study well exposed rocks analogous to those present in the sedimentary basins of the Barents Sea.

Four gabbroic and dioritic samples from dykes cutting apparent Devonian sedimentary rocks in Matotchkin Strait and Mashigin Fiord were processed, analyzing zircon and titanite for U-Pb by the ID-TIMS technique. The results were unexpected as all four samples yield Late Precambrian ages, rather than the anticipated Mesozoic ages. Except for local inheritance linked to visible cores in zircon, there is no reason to believe that the populations could be xenocrystic. The zircon crystals are of uniform appearance with the long-prismatic and skeletal shapes typical of populations in mafic rocks and, in one sample, the zircon age is corroborated by that of coexisting titanite. The two samples from Mashigin Fjord yield slightly different ages of 716 ± 8 and 704 ± 5 Ma whereas those from Matotchkin Strait are identical at 707 ± 2 and 706 ± 14 Ma.

Although the new ages do not confirm the previously proposed chronostratigraphic position of the samples, they are not unreasonable when considered in their regional context. In fact Korago et al. (2004) have reported a similar age of ca. 700 Ma for the Mutushev granite, just north of Matotchkin Strait. That particular granite is overlain unconformably by Silurian strata (Korago et al. 2004) suggesting that the intrusives dated in our study may also fit in a similar basement –cover setting. The same authors reported zircon U-Pb ages of ca. 600 Ma for granites at Sulmenev Bay north of Mashigin Fiord, again confirming the presence of Vendian intrusives, this time cutting Mesoproterozoic basement. On a larger scale, the Neoproterozoic activity of Novaya Zemlya links up to events that had strong influence on the geology of the Uralian and west-Siberian regions. The 700-720 Ma put this activity ahead of the Timanian convergence and collision; its timing fits best with that of arc magmatism and ophiolites generation on the Siberian margin (e.g. Vernikovsky et al. 2003). The data are thus a very relevant contribution to the further development of the post-Rodinian Torsvikian continental reconstructions.

References

Holtedahl, O. 1924. On the rock formations of Novaya Zemlya. Report of the scientific results of the Norwegian expedition to Novaya Zemlya 1921 No. 22, 183 pp.

Korago, E.A., Kovaleva, G.N., Lopation, B.G. & Orgo,V.V. 2004. The Precambrian rocks of Novaya Zemlya. In Gee, D,G, & Pease, V.L. (eds.) The Neoproterozoic Timanide Orogen of Eastern Baltica. Geol. Soc. London Memoirs, 30, 135-143.

Nakrem, H.A. & Gradstein, F.M. 2007. Novaya Zemlya – the Holtedahl 1921 expedition and the valuable collection of rocks from an inaccessible part of the Russian Arctic. NGF Abstracts and Proceedings, no. 1, p. 67.

Svensen, H., Planke, S., Malthe-Sørenssen, A., Jamtveit, B., Myklebust, R., Eidem, T., & Rey, S. S. 2004. Release of methane from a volcanic basin as a mechanism for initial Eocene global warming. Nature 429, 542-545.

Vernikovsky, V.A., Vernikovskayaa, A.E., Kotov, A.B., Sal'nikova, E.B., & Kovach, V.P. 2003. Neoproterozoic accretionary and collisional events on western margin of the Siberian craton: new geological and geochronological evidence from the Yenisey Ridge: Tectonophysics 375, 147– 168.

5.10 Circum-Arctic Mapping Project: New magnetic and gravity anomaly maps of the Arctic

Carmen Gaina[1] and CAMP-GM group[2]

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An international effort to compile Circum-Arctic geophysical and bedrock data is currently being conducted by several national agencies (Russia, Sweden, Finland, Denmark, USA, Canada and Norway). This project aims to produce an atlas that will comprise geological and geophysical digital maps at a scale of 1: 5 million for the Arctic region limited by the 60 degree North latitude.

New published and formerly classified magnetic and gravity anomaly gridded data from each participant group were gathered and converted to a common datum and format. The magnetic anomaly compilation relies on 1 km gridded data for Canada (based on the Canadian Aeromagnetic Data Base), Alaska (based on Alaska USGS aeromagnetic database) and NW Europe (Fennoscandia compilation and the NGU NE Atlantic compilation) regions, and 5 km gridded data for oceanic and Russian regions. The grids have been merged using two separate methods: the GEOSOFT routine GridKnit and an alternative method proposed by Hemant et al (2007). The final grid resolution of this compilation will be 2x2 km upward continued to 1 km. Preliminary Circum-Arctic magnetic anomaly maps will be presented and technical details will be discussed.

The planned gravity anomaly compilation includes one map of the Free Air gravity anomaly for the Circum-Arctic region and one map of combined Free Air ***(for oceanic area)*** and Bouguer ***(for land)*** anomalies, both at 10x10 km grid resolution. Satellite gravity models are used for quality control on the long wavelengths of the new compilation.

References

Hemant, K., Thebault, E., Mandea, M., Ravat, D., and Maus, S. Magnetic anomaly map of the world: merging satellite, airborne, marine and ground-based magnetic data sets, Earth and Planetary Science Letters (in review).

Verhoef, J., Roest,W.R., Macnab, R., Arkani-Hamed, J., et al., 1996. Magnetic anomalies of the Arctic and North Atlantic Oceans and adjacent land areas. Geological Survey of Canada. Open file 3125a (http://agcwww.bio.ns.ca/pubprod/of3125etc.html), Canada.

5.11 Constraining the history of the North Atlantic Igneous Province: new constraints from the Isle of Mull, Scotland.

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Large Igneous Provinces, overwhelmingly of basaltic affinity constitute the surface expressions of catastrophically rapid dissipation of large quantities of internal heat. Subsequent to their extrusion, most LIPs have changed position in the Earth's surface due to plate motions. With an estimated volume of ca 10^7 km^3, the North Atlantic Igneous Province (NAIP) represents the 3rd largest magmatic event on Earth during the last 150 Myr. The NAIP formed during two major magmatic phases: a pre-break-up phase (62-58 Ma) and a synbreakup phase (56-54 Ma) contemporaneous with the onset of North Atlantic sea floor spreading. The formation of the NAIP has been linked to the proto-Icelandic plume through paleogeographic reconstructions and geochemical observations. Since the late 1980's much of the research focus on the NAIP has been guided by the understanding of the genetic relationship between North Atlantic magmatism that began in the earliest Palaeocene, the genesis/position of the Iceland Hotspots and/or related mantle plume(s) through the Cenozoic, and the change at ~54 Ma from a long period of continental rifting and thinning of sea-floor spreading. However, despite the number of data available, the temporal and physico-chemical ties between NAIP rocks, hotspot motion and continental break-up have not been demonstrated to fit a single regionally applicable and consistent geodynamic model. For example, discrepancies between recent palaeomagnetic poles from Western Greenland and the Faeroe Islands (Riisager et al. 2002, 2003) and older data from the British Tertiary Igneous Province (BTIP) have questioned the reliability of the latest. Therefore, to ultimately understand the tertiary evolution of the North Atlantic, extensive palaeomagnetic and $^{40}Ar/^{39}Ar$ sampling on the lava fields of the British Igneous Provinces (Isle of Skye, Isle of Mull, Antrim Plateau) has been initiated. New paleomagnetic data from Isle of Mull gives a pole position at 73.3°N, 166.2°E (dp = 5.2, dm = 7.0) for Eurasia at 59 ± 0.2 Ma. This is in accordance with most of the palaeomagnetic poles from the BTIP and thus confirms the reliability of previous studies. A re-evaluation and an inter-comparison of the palaeomagnetic database emanating from the NAIP were carried out to test for sub-province consistency. We find a general agreement between the Eurasian part of NAIP (BTIP and Faeroes) and East Greenland data. However a compilation of West Greenland data displays a large and unexplained dispersion. We speculate on if this is related to different sense of block rotation of the Tertiary West Greenland constituents. Combining all data from the NAIP constituents, give a pole position at 75.0°N, 169.9°E (N = 25, K = 84.3, A_{95} = 3.2).

5.12 Syn-and post-breakup magmato-tectonic evolution of the mid-Norwegian volcanic rifted margin

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The mid-Norwegian margin is probably one of the best examples worldwide of rifted volcanic margins. In order to refine the structure and tectonic evolution of the margin, a 120000 km^2 new aeromagnetic survey (JAS-05) was acquired along the trend of the Jan Mayen Fracture Zone, west of the Vøring Marginal High. This acquisition is part of a larger ongoing project aiming to fully map the Norwegian-Greenland Sea with modern aeromagnetic data. The difference between this new survey (5x20 km; Line/Tie line spacing) and old aeromagnetic data is significant and definitively provides both new magnetic framework and insights on the geodynamic evolution of the Norwegian-Greenland Sea. The main faults, structure and magnetic anomalies have been re-interpreted using a systematic and detailed comparison between high-resolution bathymetry, gravity, magnetic patterns and seismic data. Magnetic chrons are now better identified, new anomalies have been detected and the fault pattern has been refined. Data and interpretation illustrate and document the syn- and post-breakup magmato-tectonic evolution of the margin. Anomalous melt production associated with the breakup of the volcanic margin is well known (Seaward Dipping Reflectors, underplating, sill intrusions). The new data reveal, however, that anomalous igneous activity continued episodically and extensively along the trend of the JMFZ, as suggested by local overcrusting processes (oceanic crust up to 15 km!). To explain this atypical magmato-tectonic process, we suggest a challenging geodynamic model. Plate reconstructions, show that a triple junction could have initiated during the breakup between the Vøring Marginal High and a prominent magnetic anomaly, offshore Greenland, so called the Traill-Vøring igneous complex. Mantle upwelling under the early spreading ridge and/or local stress reorganisation could have induced transtension and lithospheric thinning along the JMFZ. Magmatic activity could have increased locally and episodically along this "leaky transform". This early tectono-magmatic process can be compared to the Azores Plateau, which can be used as a modern "analogue" to the early Norwegian spreading system initiated at C24B (54-53 Ma ago) or may be earlier as suggested by intriguing magnetic anomalies interpreted as C25 (?), south of the Jan Mayen Fracture Zone. The JAS-05 also questions the validity of real volcanic SDRs along the northeastern margin of the Jan Mayen microcontinent. They may most likely represent sedimentary rotated fault blocks, only overlapped by a thin basaltic layer. We thank the Norwegian Petroleum Directory, Statoil and Shell Norge for financially supporting the JAS-05 project.

5.13 A Paleomagnetic Paradox from the Tarim Basin, China

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New Permian and Middle Jurassic paleomagnetic data from the Tarim Basin pose a paradox. Their declinations are identical to Upper Carboniferous to Neogene rocks collected from the same section, and their inclinations are similar to today's. When assuming that lower than expected inclinations in continental sediments arise from inclination shallowing effects, then the paleolatitudes of all Upper Carboniferous to Present rocks from Tarim are indistinguishable. After accounting for local vertical axis block rotations occurring in the last 20 million years, these observations suggest that Tarim experienced no apparent polar wander since the Carboniferous. Our Middle Jurassic pole positions Tarim 23.6±8.4° farther south than that predicted from the coeval reference pole for Eurasia; however, no geological argument exists to support the closure of a large ocean basin between Tarim and Siberia since the Middle Jurassic. Thus the paradox: are the rocks from Tarim overprinted, or is the Middle Mesozoic part of the Eurasian apparent polar wander path erroneous? Several lines of evidence suggest the Tarim data are not overprinted. We conclude that Tarim has experienced little or no apparent polar wander since the Carboniferous. Moreover, we propose a new Middle Mesozoic reconstruction of Eurasia using the new Middle Jurassic pole from Tarim. Our reconstruction results in a more geologically compatible solution for the eastern Asian blocks over previous reconstructions.

5.14 Assimilation of plate tectonic reconstructions into regional and global models of mantle convection.

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To motivate the present work, we start with the not so classic, but nevertheless interesting work by *Gurnis and Tosvik* [1994]. Here, we see the motivations, both paleomagnetic and modelling, needed to move forward with the Revolution proclaimed by the Osama Redfield[1]. Here, we see the germ of the idea that a subtle balance can drive plate motions between the intricate geometry of the buoyancy forces and the even more intricate details of plate and mantle theology[2]. *G & T* were able to show that continental keels would speed up plate motions if the forces driving the plates rested in the deep belly of the mantle, but slowed if pulled by subducted slabs. Being, two-dimensional toy models, and not predicting the motions of actual plates, such as the famed Baltica or the less famed California, our esteemed colleagues around the world largely ignored these words of wisdom.

Overcoming the limitations of these toy models begins the story of CitcomS and GPlates. The former is not a mere situational comedy, but a finite element 'Code' capable of leapfrogging the limitations of toy models, including theological limitations. In the true spherical geometry of the mantle, with CitcomS we can solve for the rapid variations in theology that occur laterally and radially in the lithosphere and mantle. CitcomS was mostly the product of two brilliant colleagues, Louis Moresi and Shijie Zhong who are now professors at Monash University and the University of Colorado, respectively. So, as only attempted earlier in toy models, we can place both the realistic geometry of the driving and resisting forces into the spherical models. Unfortunately, the pinnacle of greatness that should be bestowed upon the Code has yet to be achieved.

In the humble opinion of this computer modeller, global plate tectonic reconstructions are inadequate for geodynamics, either as information to be assimilated into a model or as the basis to map a prediction into the geological record. Although not likely to be the case for maps produced by my esteemed colleagues participating in the First Trond Helge Torsvik Symposium on the Fourth Revolution in the Earth Sciences, other published reconstructions are often crudely spaced in time, have large swaths of the surface ambiguously defined, and/or have plate margin evolution inconsistent with plate motions.

[1] It is rumoured that Osama from the far north, reborn as a true Nordic sailor, once wrote "In the 1960s the earth sciences underwent the plate tectonic revolution. Today, it is increasingly well-recognized that mantle dynamics represent a 'fourth revolution.'"

[2] Often mistakenly referred to as rheology.

So was born my own interest in GPlates. As you all know, the G is for greatness and not for the alleged "Global" and certainly not for "Gnu". It is for the greatness we might achieve with this new "Code" that we long ago bestowed GPlates with its name. Now I do realize that there is snickering in the back alleys of the Halls of Science suggesting that the true sitcom is GPlates and not Citcom. Slowly, but surely, we have overcome the obstacles holding us back with the formulation and implementation of a new method to represent plate tectonic reconstructions. Referred to as either "continuously closing" or "dynamically closing" plate polygons, the new method has been implemented using the first version of GPlates, the so-called zero point eight. The closure methods were invented and implemented by Caltech software engineer Mark Turner. But the innards of this method were mostly designed and implemented by Sydney software engineer James Boyden. In fact, James has since completed the innards of the new redesigned Code. Over the last six or so months, global reconstruction have been developed with the method, and then reconstructions have been assimilated into forward and adjoint mantle convection models. Many individuals have toiled away creating these reconstructions. Of course, it goes without saying that we have worked closely with Dietmar Müller of Sydney University on the new reconstructions and have strived to make the reconstructions consistent with the paleo age grids developed by Maria Sdrolias at Sydney and Carmen Gaina at NGU.

Essentially, a plate is defined as a polygon that is made up of a finite set of plate boundaries. Each plate boundary has is own Euler pole. These plate boundaries are continuously rotated and an algorithm finds the intersection of adjacent plate boundaries. Two adjacent plates always share a boundary. Using this method in GPlates, we have developed several global plate reconstructions from 140 Ma to the present. Since plate closure is continuous in time, reconstructions can exist at any granularity of time. Our present model has been output at 1 Myr time intervals. Subduction zones and their polarity are continuously tracked. We will illustrate the use of the new reconstructions in several applications drawn from our recent work: (1) regional subduction models; (2) global models of thermo-chemical convection in the lower mantle; (3) inverse and adjoint models of the descent of the Farallon slab; and (4) instantaneous models of global plate motions. We haven't yet to redo the calculations in *G & T* using these new methods, but its just a matter of time before we have Trond's famed Baltica zipping back and forth over the surface of a sitcom re-run with variable theology.

References

Gurnis, M., and T. Torsvik, Rapid drift of large continents during the Late Precambrian and Paleozoic: Paleomagnetic constraints and dynamics models, Geology, 22, 1023-1026,1994.

5.15 Paleomagnetic studies on mafic dykes and U – Pb age data on rhoylitic tuff in the Malani Igneous Suite, NW India: Implications for the configuration of Rodinia

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The configuration of the Precambrian supercontinent Rodinia and the subsequent assembly of Gondwana are under considerable debate due to a paucity of high quality paleomagnetic data from some critical terranes. The Indian subcontinent is crucial to this topic and plays an essential role in the history of East Gondwana amalgamation. In proto-Gondwana reconstructions the location of the central Indian craton is important in testing the existence and age of the proposed Rodinia supercontinent. Improved paleomagnetic and geochronologic data collected from numerous dikes in central India will help to better constrain the details of this supercontinent.

Malani Igneous Suite in NW India is predominantly composed of felsic rocks which include initial voluminous rhyolitic flows (at places bimodal in the lower part), shortly intruded by peraluminous (Jalor type) and peralkaline (Siwana type) granitic plutons and felsic dykes while mafic dykes represent the terminal phase of magmatism. We have collected samples from 4 late stage mafic dykes (from cm scale dykelet to 5 m wide) that intrude Jalor Granite. Previous age constraints from the MIS are either reported as personal communications or are unreliable and contradictory Rb/Sr dates and do not provide a complete picture of the tectonic evolution of the terrane during the Rodinia breakup. We have carried out sixteen U/Pb analyses on 10 zircon crystals from the rhyolitic tuff by secondary ion mass spectrometry and obtained concordia age of 771 ±5 Ma (MSWD = 1.5). This age is interpreted as the timing of magmatic crystallization of the rhyolite and initiation of volcanic activity. Our paleomagnetic studies on the mafic dyke samples yield a paleomagnetic direction with declination=349.8° and inclination=64.1° (k=116.4 and $\alpha 95$=11.5°), that overlaps with previously reported results. In addition, fine-grained mafic dykelets show reversed directions with a declination=195.3° and inclination=-59.7° (k=234.8 and $\alpha 95$=8.1°) and also record an overprint of normal polarity from the larger dykes. These data combined with a baked contact test truly solidify the paleomagnetic pole, and thus give insight into the complicated Proterozoic history of India.

5.16 Different magnetic fabric found in sills from the Diabasodden suite (Early Cretaceous), Svalbard located inside and outside an area of early Tertiary tectonic activity.

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Anisotropy of magnetic susceptibility (AMS) provides an estimate of the preferred orientation-distribution of minerals. In the Diabasodden suite magnetite preferred dimensional orientation are reflected in the alignment of minimum and maximum susceptibilities. Halvorsen (1974) measured the AMS of rocks of the Diabasodden Suite in eastern Svalbard outside the area affected by Tertiary tectonic activity. The magnetic foliation plan (assumed to coincide with the flow plane in the sill) was found to be close to the horizontal plane in the Lomfjorden sill and the Bastian and Rønnbeck dolerite island. Within the magnetic foliation plan the distinction between the maximum (K1) and intermediate (K2) susceptibility axes was not so clear. Both structures investigated reveal a similar but quite week preferred orientation of the K1 axes in the E-W direction and K2 axes in the N-S direction. The study is now extended to the Isfjorden area in central Spitsbergen inside the area of tectonic activity. Samples were collected in three main areas: The Hatten-Diabasodden area, the Ekmanfjorden-Dicksonland area and the Gåsøyane-Gipshuken area. The latter is situated very close to the Billefjorden fracture zone (BFZ) while the other two have a position further away from the fracture zone. Samples were also collected in the De Geer dalen which lies close to the BFZ. The results of the AMS study can be described as follows:

1. The Hatten-Diabasodden locality reveal scattered distribution of the K1, K2 and K3 susceptibility axes with a week preferred orientation of the K1 axes in the N-S direction.
2. The Ekmanfjorden-Dicksonland locality showed scattered directions with no preferred orientation of the susceptibility axes.
3. AMS measurements on samples from the Gåsøyane-Gipshuken locality revealed triaxial orientation of the susceptibility axes. K1 directed towards the east dipping with shallow angles. K2 pointing towards the south nearly flatlying and K3 nearly vertical. The sill sampled on Gipshuken is folded. The age of the folding is probably Early Tertiary. When corrected for folding the K1 and K2 axes move to the horizontal while the K3 axes become nearly vertical. A few samples show exchange of the K2 and K3 axes.
4. The orientation of the susceptibility axes measured on samples from the De Geer dalen locality show that K2 and K3 axes defines a planar magnetic fabric trending N-S with the K2 axes concentrating in the vertical direction while the K3 axes show low to moderate plunge values. K1 defines a lineation in the E-W direction.

The results of the investigation reveal a significant difference in the orientation of the magnetic susceptibility axes between the area outside and inside the region of Tertiary tectonic activity. In the Hinlopenstretet (eastern Spitsbergen) the orientation of the AMS axes defines a horizontal magnetic foliation plane which parallels the bedding in the intruded sediments. The results from the measurement of the samples collected in the Isfjorden area gives a quite different picture. The orientation of the susceptibility axes in samples collected far from the fracture zones display scattered AMS results with no preferred orientation. This is interpreted as irregular magma flow due to the great thickness of the sills in this area. The

AMS orientation found in samples collected close to the Billefjorden Fracture Zone show an E-W lineation caused by preferred orientation of the K1 axis. The K2 and K3 axes define a planar fabric in which the K2 and K3 axis shows variation between vertical and horizontal orientation. This magnetic fabric is interpreted to be caused by E-w transtension in the early Tertiary caused by interacting of Svalbard and Greenland during Arctic sea floor spreading.

References

Halvorsen E., The magnetic fabric of some dolerite intrusions, Northeast Spits Bergen; implications for their mode of emplacement, 1974. Earth and planetary Sci. let., 21, 127.133.

5.17 ~560 Ma and ~300 Ma Re-Os ages constrain Neoproterozoic glaciation and record Variscan hydrocarbon migration on extension of Oslo rift

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The Moelv tillite, exposed in the Lower Allochthon of the Scandinavian Caledonides represents the Neoproterozoic Varanger glaciation, which is generally correlated with the ~580 Ma Gaskiers glaciation in Laurentia. To refine a 620 ± 14 Ma maximum age for the Moelv tillite based on detrital zircons [1], Re-Os data were collected from a C-rich shale horizon in the Biri Formation underlying the tillite.

East of the town of Biri, the weakly deformed Biri shale is separated from the Moelv tillite by the Ring conglomerate. The shale contains a significant silt component, minor but ubiquitous fine-grained pyrite, and an average TOC of 0.7%. Exposures in a steep bedrock stream channel (Djupdalsbekken) show little bleaching or oxidation. Seven analyses of four samples taken about 50 m below the Biri-Ring contact yield an isochron age of 561 ± 4 Ma (initial $^{187}Os/^{188}Os$ (Os_i) = 1.10 ± 0.03). Four additional nearby samples scatter slightly, but all samples regressed together still yield an age within uncertainty of 560 Ma. Re-Os data from samples taken ~3 m below the Biri-Ring contact scatter about a reference line of 600 Ma with Os_i = 1.0. Scatter may result from minor Re (and/or lesser Os loss) during recent oxidative weathering. The results support an age close to or younger than the ~580 Ma Gaskiers glaciation. Given the possibility of a fourth, post-Gaskiers glaciation, and poor constraints on the latitude of south Norway at 560 Ma, low-latitude or global glaciation indicating a “snowball earth” cannot be proven.

A second Biri locality near Øvre Rendal lies on the northern extension of the ~300 Ma Oslo rift. Here, the shale shows strong cleavage, has an average TOC of 2.7%, contains lenses of pyritic sandstone, is unusually thick, and directly underlies the Moelv tillite. Road-cut exposures are locally rusty, but fresh, black samples were obtained. Eight analyses from six samples taken in a 1-m stratigraphic interval yield model ages and an errorchron near 300 Ma with Os_i = 1. Greenschist-facies, dynamic metamorphism does not appear to disturb Re-Os in shales [2,3]. We therefore propose that heat from the ~300 Ma rifting event induced hydrocarbon maturation and migration, and that the organic material analyzed was isotopically homogenized (or introduced) during this event.

References

[1] Bingen, B., Griffin, W.L., Torsvik, T.H., and Saeed, A. (2005) *Terra Nova* **17**, 250-258.
[2] Kendall, B.S., Creaser, R.A., Ross, G.M., and Selby, D. (2004) *Earth Planet Sci Lett* **222**, 729-740.
[3] Hannah, J.L., et al (2006) *Geochim Cosmochim Acta* **70**, no. 18S, A228.

5.18 Force, energy and petrology balanced geodynamics: Rock-number symbiosis or ‘sitting between chairs’?

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Our ‘bursdagsbarn’ Trond Torsvik was a Norwegian pioneer in the borderlands between the supercontinents ‘geology’ and ‘numerical modeling’. Sometimes he explored this terrain by careful and creative thinking, sometimes by trial and error, but always by dedication. At first research in these borderlands was considered more like sitting between two chairs, than an actual symbiosis, but over the years more have ventured into this terrain. In this presentation we tour some of our own findings in this borderland between force, energy and mass (petrology) balanced numerical models, and rock-science.

In our first example we discuss the origin of ultra high pressure PT records in rocks on the earth surface, and decorate this with examples from the Caledonides. Generally pressure estimates based on equilibrium thermodynamics have been treated as equivalent to depth estimates. The concept of tectonic overpressure – challenge this view, suggesting that horizontal tectonic stresses add to the vertical gravitational stresses, in some cases doubling pressures compared to conventional gravitational (load) pressure. Here we first review the concepts of tectonic overpressure and associated shearheating, and then analyze their effects on the PT record. Such calculations depend on rock rheologies but can be tested against rheology-independent force balanced models, as well as natural rocks.

Secondly, we introduce the theoretical concept of ‘reaction overpressure’, which relates differential volume expansion of inclusions inside a stronger container to extreme and rapid PT excursions; similar to a pressure cooker. Reaction overpressure may act on any scale and differs from tectonic overpressure in that it does not require high rock strength (differential stress). Pressure builds as the rocks heats and expands, particularly as melt conditions is approached. Eventually the pressure may exceed the ‘container’ strength, which will break, leading to a catastrophic drop in (over)pressure, and subsequent pervasive decompression melting. The process is self-propagating, and results in a PT path similar to the melt lines on a PT diagram. Such dramatic and rapid PTtime loops are common in the literature and have typically been explained by rapid and deep subduction-exhumation cycles. However, considered ‘reaction overpressure’ extreme pressure records are perhaps not diagnostic of extreme depths. In support of our model, we illustrate that the PTtime excursion recorded in the UHP eclogites of Liverpool Land, East Greenland, fit this model. These rocks appear to have been positioned in the overriding plate of the Caledonian collision, and therefore need a nontraditional explanation for their calculated PT excursion, subsequent pervasive melting, and rapid cooling.

In our third example we test the effect of implicating force, energy and mass (petrology) balances into exhumation/subsidence models. For example, traditional models considering thinning/thickening and thermal expansions will dictate syn and post tectonic subsidence when the lithosphere thins, and syn and post tectonic uplift when the lithosphere thickens. Natural examples show that that this is not always the case, or at least not to the scale modeled. If we repeat our numerical experiments (thinning and thickening) and implement force balances (over and underpressure), energy balances (shear heating) and mass balances (volume of rocks controlled by thermal expansion, compressibility, and particularly mineral phase transitions) the results of our models in some cases reverse. For example we can explain the syn extensional uplift so often observed in nature.

Collectively we suggest that implementation of for examples force and energy balances in both numerical and conceptual models can offer solutions of long standing Earth Science enigmas, and thus should be more widely considered.

5.19 Different styles of deformation of the fore-arc wedge along the Chilean convergent margin: Insights from 3D numerical experiments.

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Despite almost equal plate kinematic boundary conditions along the Chilean convergent margin, the styles of deformation of the forearc wedge differ significantly from north to south. We analyse possible causes of this diversity using 3D numerical deformation modelling. The Forearc wedge along the Chilean margin is characterized by the oblique subduction of the Nazca plate, major margin-parallel strike-slip faults and the Andes mountain chain acting as a backstop. We tested the influence of various parameters, e. g. dip of slap, rate of convergence, obliquity, strength of coupling between Nazca plate and South American plate, and Young's modulus, to understand how geometries, rheologies and mechanical parameters influence strain partitioning and styles of deformation in the Chilean forearc. The numerical models are applied to a northern and a southern study area along the Chilean margin at 20°-24°S and 37°-42°S. The rates of deformation obtained from the model simulations and comparison with field data suggest that the subducting Nazca plate and the South American continent should be separated by a relatively weak subducting interface, which was implemented numerically by a contact surface with a lower friction coefficient. The analysis of strain partitioning in the forearc wedge showed that simple rheological concepts for the wedge (purely elastic or viscous) cannot represent field observables with acceptable accuracy. The elasto-plastic model wedge accommodates oblique subduction motion of the Nazca plate more realistically, which allows to compare results with observables of GPS measurements and estimate parameters of the model with considerable confidence. The coupling between the subducting Nazca plate and South America, the rate of convergence as well as the strength of the wedge material was found to have a high influence on the style of deformation. Weaker coupling is predicted for the southern study area than for the northern region. That conclusion is in agreement with observed accretive style of mass transfer in the south and erosive mass transfer in the north, respectively.

5.20 Trond and Topo Europe: A case study in… well… …something.

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Once upon a time there was an Earth.

Not a flat Earth, mind you. Nor spherical, either. "No, Best Beloved," (said Mother Jaguar, graciously waving her tail), "this Earth was an imperfect, inhomogeneous Earth. Oblate and dimpled, her crust penetrated by plutons and riven by faults, this Earth was notoriously difficult to fit into a box. You could stretch her and squeeze her and color her like so many tablecloths, but at the end of the day the True Earth behaved completely unlike her numerical counterparts. They tried, Best Beloved," (having finishing the last of the bones Mother Jaguar arched her back elegantly, sagaciously licking her chops) "but you know, I always liked real cutlets better than digital ones."

We see, probe, and study the outermost layers of the Earth. However, we tend to forget that the *face* of the Earth ~ her topography ~ reflects processes that stem from her innermost depths. From the rifting of supercontinents to the subduction of ancient, long- vanished plates, deep-Earth processes fundamentally define the surface upon which we live. Fieldwork confronts us with today's shapes ~ geometries that must be reconciled with the processes of deformation and erosion that created them. However, reconstructing the past processes that led to a particular preset-day form is commonly hindered by lack of continuous outcrop, limited depth resolution, or little to no constraints upon time. Thus modelling (in spite of Mother Jaguar!) is a fundamental tool with which to study the processes that create and subsequently alter the Earth's topography.

In the 1960s the earth sciences underwent the plate tectonic revolution. Today, it is increasingly well-recognized that mantle dynamics represent a 'fourth revolution.' In large part, mantle dynamics may only be studied with numerical models. A numerical model ~ the mathematical description of a natural situation ~ requires that those aspects of processes will be chosen that are both of interest and can be feasibly captured in equations. *("Numerical models," continued Mother Jaguar, "always imply a simplification of reality.")* Thus, the integration of models with hard data ~ field-based observations that range from plate kinematics to glacial morphology, thermochronology, and classical structural geology ~ represents the only direction in which advances in our understanding of the development and maintenance of topography may be made.

TopoEUROPE will be empowered by the natural integration of multiple disciplines. For example, the Scandinavian Mmountains rise asymmetrically from the ancient Mesozoic margin, their western escarpments shaped by structures inherited from the great Baltica-Greenland rift event. Their eastern slopes descend to the Gulf of Bothnia on a decreasing gradient matched by an increase in fission track age, a gentle warp fundamentally controlled by the flexural rigidity of the Scandinavian lithosphere. In Finland ~ Baltica's Heart of Darkness ~ the AFT ages go berserk, reflecting a topographic longevity with no vestige of a beginning and no prospect of an end. Like the best of jewellers, the Ice Ages left behind a world-class finish: Alpine, vidda, valley, and other landscapes were inscribed on the weather-beaten bones of this most ancient of shields. And still she rises! Landslides and earthquakes belie the ‘passive’ nature of the circum-Atlantic margin, periodically reminding us of demons inside. Some fifty five million years after the onset of sea floor spreading Norway’s mountains still live, and it is our challenge to figure out why. Under the umbrella of TopoEUROPE, Trond Helge Torsvik will do his best to oblige.

5.21 Observations about continental crustal thinning inferred from Reflection and Refraction Seismic Data Analysis on Central Atlantic margins

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The mechanism that leads to dramatic crustal thinning of passive continental margins as well as the inception of oceanization is still a matter of debate. Recent studies on passive margins show that further progress in this subject is acquired only by an integrated study of conjugate margins placed in a kinematic framework.

Here we present a structural analysis of the Central Atlantic margins based on reflection and refraction seismic data collected during the Dakhla cruise (2002), on the South Morocco margin in front of Reguibat, and a compilation of existing comparable datasets (reflection and refraction data) from the North American margin and the Moroccan Meseta.

Margins can be divided in four zones. Zone I corresponds to the continental platform domain. Zone II is the continental slope domain. Zone III is an atypical oceanic crustal domain, between the foot of the continental slope and what can be unequivocally defined as the oceanic crust. Zone IV is the typical ocean crust domain. Zone II (the continental slope domain) shows two structural regions: 1- The data clearly indicate that crustal thinning is abrupt (except at the Dakhla site), not wider than about 60 km and limited to the continental slope. In this part, continental crust thins from around 30 km to less than 10 km and we do not observe any extensional structures. 2- At the bottom of the continental slope, the crust is completely thinned and stretched.

Classical margin formation models imply a continuous thinning of the entire crust from the hinge line. Contrary to this model, our observations show that the thinning occurs without upper continental crust break and only on the distal part of the margin.

5.22 Abstract not available

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5.23 Breaking up: Fault gouge evolution during shear

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To better understand fault zone dynamics we need an improved understanding of the underlying micro-mechanics of the fault evolution process. Our basic data is gleaned from quantitative observations of structural fabrics associated with natural fault systems. However, such datasets generally record the final state of evolution, from which it is often difficult to discern the dynamic micro-scale processes involved or the macro-mechanical behaviour of a fault. Laboratory experiments give valuable insights into links between microscale processes and macro-mechanical behaviour. Similarly, numerical simulations are very useful tools for visualising dynamic grain-scale interactions not readily visible from nature. Together these tools can help us identify and isolate first order parameters that are relevant for the faulting process.

We present new 3D simulations that implement realistic gouge evolution during shear. Our particle based simulation includes breakable elastic bonds between individual particles allowing fracture of aggregate grains that are composed of many bonded particles. With accumulated strain, aggregate grains gradually evolve in size and shape to produce a textural signature reminiscent of natural faults. We use a new image analysis tool to characterise grain shape and size distributions from thin sections obtained from natural and experimental fault rocks. This tool utilises a greyscale thresholding method to identify and characterise individual grains. We use similar techniques to quantify synthetic 2D sections from our 3D numerical model outcomes. This approach allows us to build on existing observations and permits closer investigation of dynamic processes that may be operating in evolving fault zones.

5.24 Stressing, bending, and stretching Trond's (g)plates

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Once upon a time four men come together to think how they should live further.

"Let's make something simple and good-looking!" said one of them. "Let it be connected to the Great North, I like Cold!" said the second. "It will be the best in the World, we will show to others what they have overlooked!" said the third. "Sure". The last man did not talk much because he was the wisest of those four. He was very old, but nobody knew how old, because in this land people could only count until 49 …

In order to address the numerical challenges of modelling Arctic deformation we have developed the first version of ProShell. It is similar to traditional thin-sheet approximations and based on the analytical treatment of the vertical balance of forces, but in addition this new approach balances the bending moments and resolves the 3D geometry of the lithospheric shell. ProShell is a finite-element based numerical code in which each finite element represents a small shear deformable platelet with membrane properties. The ProShell approach balances the integrated forces and moments within each element and along its boundaries. Furthermore it calculates bending and thickness change inside each element. The curvature of the model geometry may result in the transformation of bending (temporary deformation) in one element into thickening (more permanent deformation) in the neighbouring element. This property is important in modelling large-scale deformation on Earth and it is not present in any previous model. A significant part of the ProShell approach is the way it deals with data. A set of routines is designed to allow easy data adaptation and operation in the context of data analysis, FEM calculations, and plate reconstructions.

Within the initial development of ProShell its basic concepts have been validated. A major aim of ProShell is to understand the importance of 3D geometry and curvature. We have therefore tested the effects of tectonic forces on the deformation patterns in the Earth's lithosphere resulting from the various approximations. The model was implemented on a flat, a smooth spherical, and a spherical Earth with topography ("crumpled Earth"). The crumpled Earth model predicts amplification of stresses in the areas of high local curvature associated with the Earth topography. In particular, it predicts extensional stress along the eastern margin of Greenland and compression along the western Barents Sea shelf. These results especially emphasise the importance of topography as the changes between flat and spherical smooth plate models are minor

5.25 India's changing place in global Neoproterozoic reconstructions: New Geochronologic constraints on key paleomagnetic poles

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The East Gondwana terrane is comprised of India, Australia, East Antarctica, Madagascar and Sri Lanka. Knowledge regarding the assembly of East Gondwana and its later amalgamation into Gondwana requires well-dated paleomagnetic poles. Madagascar, Sri Lanka and the exposed regions of East Antarctica are cut by numerous orogenic belts related to Gondwana assembly and therefore target rocks in these regions are poor candidates for paleomagnetic study. In contrast, both Australia and India contain numerous unaltered sequences that may be used to establish their drift histories prior to the final fusion of Gondwana.

In the past 3 years we have focused on improving the Meso-Neoproterozoic drift history of India by focusing on obtaining robust paleomagnetic and geochronologic data from key sedimentary and igneous sequences in India. Specifically, we have conducted studies on the presumed Neoproterozoic-Cambrian age Upper Vindhyan sedimentary sequence in central India, the 771 Ma Malani igneous province in Rajasthan, the ~1100 Ma Majhgawan kimberlite that intrudes the lowermost Upper Vindhyan rocks and the ~823 Ma Harohalli dikes in southern India. Each of these had been the focus of previous paleomagnetic studies, but the geochronologic constraints were only poorly known. The generally accepted sequence of paleomagnetic poles was (from oldest to youngest), the ~1100 Ma Majhgawan kimberlite, the ~823 Ma Harohalli dikes pole, the 771 Ma Malani igneous province pole and the Neoproterozoic-Cambrian Upper Vindhyan pole.

We will report new paleomagnetic, geochronologic and detrital zircon age distributions that require a drastic revision in the apparent polar wander path for India. We show that the new sequence of poles (from oldest to youngest) is ~1200 Ma for Harohalli, ~1070 Ma for both the Majhgawan and Upper Vindhyan poles, 771 Ma for the Malani igneous province and an magnetic overprint of Ediacaran age observed in dikes in southern India (including Harohalli).

5.26 Farallon-Izanagi-Alaska plate motions, trench and ridge subduction offshore Alaska during the Cretaceous

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We present a framework for the tectonic development of the Arctic region through a set of global plate and ocean floor reconstructions since the early Cretaceous. In order to understand the effect of time-dependent geometries of mid-ocean ridges, subduction zones and collisional plate boundaries on Arctic basin evolution and reactivation through time, we reconstruct now subducted ocean floor, including portions of tectonic plates which have now entirely vanished, and restore their plate boundary configurations and subduction history. We reconstruct paleo-oceans by creating "synthetic plates", the locations and geometry of which are established on the basis of magnetic lineations and fracture zones, geological data and the rules of plate tectonics. The absolute position of the Pacific Plate and its surrounding plates is restored using a Pacific hotspot reference frame, whereas all other plates are reconstructed based on an African-Indian hotspot reference system. This approach is required because the Pacific Plate was entirely surrounded by subduction zones in the Cretaceous, and therefore Pacific Ocean plates cannot be related to other tectonic plates via relative plate motions. Our reconstructions reveal that the Izanagi Farallon spreading ridge was subducted underneath Alaska from about 120-100Ma. Prior to 120 Ma the northern portion of the Izagani-Farallon plate boundary was a convergent boundary according to our reconstructions, implying that between 140 and 120 Ma a subducting slab was overridden by the Alaskan North Slope and possibly other associated terranes. The Izanagi-Farallon subduction zone (before 120 Ma) and midocean ridge (after 120 Ma) was oriented roughly orthogonal to the overriding plate. Trench subduction would have been associated with negative dynamic topography on the overriding plate, whereas an eastward migrating slab window underneath North Slope and its border terranes may have resulted in asthenospheric upwelling and extension. Mid-Cretaceous (Aptian to Santonian) rocks are missing over much of the Alaska Peninsula, presumably eroded, and the widespread absence of rocks of this age suggests uplift and erosion of the entire terrane during a portion of Aptian to Santonian time (Wilson et al., 1999). These observations generally support our model, but the relative roles of trench and ridge subduction for causing the widespread regional erosion or for triggering the opening of the Canada basin remain open.

References:

Wilson, F.H., Detterman, R.L., and DuBois, G.D., 1999, Digital data for geologic framework of the Alaska Peninsula, southwest Alaska, and the Alaska Peninsula Terrane, USGS Open-File Report 99-317.

5.27 Aeromagnetic remapping of the Norwegian Sea

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Remapping of the oceanic crust in the Norwegian Sea with improved magnetometers and navigation during the last four years has improved our under-standing of the Early Tertiary opening of the North Atlantic.

Palaeogeographic reconstruction of the aeromagnetic map to Anomaly 22 reveals a c. 50 km wide magnetic anomaly cutting across spreading anomalies 24A, 24B and 23 from the Vøring Marginal High on the Norwegian margin to Traill Ø on the East Greenland coast. The anomaly is interpreted to represent an igneous complex referred to as the Traill-Vøring igneous complex (TVIC). Offshore Greenland, the complex crosscuts anomaly 22 on the margin, suggesting that the igneous activity was active until c. 50 Ma. This magmatism may be associated with a previously proposed NNE-trending initial magmatic lineament (IML) extending between Traill Ø and Kangerlussuaq. The IML has been suggested to relate to a failed attempt of direct linkage between the Reykjanes and Mohns Ridges. The magnetic response of the TVIC along the Vøring margin has previously been interpreted as representing anomaly 24A and 24B. Interpretation of a more recent aeromagnetic survey along the Jan Mayen Fracture Zone has revealed that he TVIC may represent the leaky transform part of a pseudo triple junction resembling the present day tectonic situation observed on the Azores Plateau in the central Atlantic.

Tectonic reconstruction using the new aeromagnetic datasets has also shown that the opening of the Norwegian-Greenland Sea between the Jan Mayen and Senja fracture zones occurred along a stable axis without offsets of the oceanic spreading anomalies and without jumps in spreading axis. Transfer zones have previously been associated with oceanic fracture zones along the Mid-Norwegian and East-Greenland margins. NGU’s new aeromagnetic data clearly shows that these fracture zones were artefacts caused by navigation errors and other problems of the vintage data. Transfer zones are usually interpreted as important entry points for sedimentary drainage systems, and a relationship that has also been suggested for the transport of Cretaceous and Paleocene sands to the mid-Norwegian margin. Our new interpretation can consequently have implications for evaluating the reservoir distribution in the Vøring Basin.

5.28 Paleomagnetism and Geochronology of the Malani Igneous Suite, Northwest India: Implications for the configuration of Rodinia and the assembly of Gondwana

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The configuration of the Precambrian supercontinent Rodinia and the subsequent assembly of Gondwana are under considerable debate due to a paucity of high quality paleomagnetic data. The Indian continent is crucial to this topic and plays an essential role in the history of East Gondwana amalgamation. In proto-Gondwana reconstructions the location of the central Indian craton is important in testing the existence and age of the proposed Rodinia supercontinent. Improved paleomagnetic and geochronologic data collected from numerous dikes in central India will help to better constrain the details of the supercontinent. We have collected samples from 4 late stage mafic dikes that intrude the Jalore Granite in the Malani Igneous Suite (MIS) in Rajasthan, Central India. The MIS is primarily composed of felsic rocks that erupted in initial voluminous flows, which were shortly intruded by granitic plutons. The large (up to 5 m wide) mafic dikes mark the final phase of igneous activity and were the targets of our investigation. Previous age constraints from the Malani suite are either reported as personal communications or are unreliable Rb/Sr dates and do not provide a complete picture of the tectonic evolution of the continent during the Rodinia breakup. We obtained a paleomagnetic direction with declination=349.8° and inclination=64.1° (k=116.4 and α95=11.5°), that overlaps with previously reported results. In addition, fine-grained mafic dikelets show reversed directions with a declination=195.3° and inclination=-59.7° (k=234.8 and α95=8.1°) and also record an overprint of normal polarity from the larger dikes. We also report an U/Pb age of 771 ±5 Ma from zircons in the Malani rhyolitic tuff These data combined with a baked contact test truly solidify the paleomagnetic pole, and thus give insight into the complicated Proterozoic and Early Cambrian history of India.

5.29 Present-day stress orientations in Norway as deduced from stress-release features and active, post-glacial reverse faulting

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Fieldwork was conducted in different parts of Norway -- Finnmark, Trøndelag and the Oslo Region -- with the purpose of detecting and measuring stress-relief features, induced by quarrying and road works, and to derive from them valuable information on the shallow-crustal stress state. These investigations followed the earlier discovery of the currently active, post-glacial Stuoragurra Fault in northern Norway, a reverse fault that was the locus of a 4.0 magnitude earthquake in 1996. Two kinds of stress-relief features were considered in this study. The first consists of drillhole offsets that were found along blasted road-cuts and which were triggered by the sudden rock unloading following the actual blasting. Vertical axial fractures found in the concave remains of boreholes represent the second kind of stress-relief feature. The axial fractures are tension fractures produced by gas overpressure inside the drillhole when the blast occurs. As such, their strike reflects the orientation of the ambient maximum horizontal stress axis. Stress release- features are less common in the Oslo Region than in Finnmark or in Trøndelag, suggesting that stress magnitudes at shallow depths in the Oslo Region are lower than in the two latter regions. In Finnmark, mechanical considerations of the slip planes offsetting some of the drillholes lead to the conclusion that the magnitude of the maximum horizontal stress at the surface is in the range ~0.1 to ~1 MPa. In Trøndelag, the Møre-Trøndelag Fault Complex appears to separate two distinct stress provinces, as already suggested by previous numerical modelling studies. In the three studied areas, the borehole offsets show mostly reverse-slip displacements to the E-SE and the axial fractures trend NW-SE on average, in agreement with NW-SE compression induced by North Atlantic ridge-push forces. Isolated observations of reverse-slip displacement of drillholes in other parts of Norway also show the same general compressional trend.

5.30 Some thoughts on the immovability of the Trond anomaly

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100 years ago Alfred Wegener proposed that the centrifugal force moved the heavy continents toward the equator as the Earth spun. He thought that inertia, from the centrifugal movement combined with tidal drag on the continents (caused by the gravitation of the sun and moon), would account for continental drift. Tidal drag was estimated as too small. Inertia of thinking stopped scientists to accept the rest of the story and the continents were stopped.

50 years ago Trond was born and, coincidentally, continents revived their drift in the brains of geoscientists, now called plates. While his adviser is still trying to stop continental drift in its present form of plate tectonics, Trond, using plate tectonic tools, has managed to stop moving, both vertically and horizontally, the low velocity zones in the lowermost mantle, located at the equator of the Earth.

This zone was called an anomaly to start with. The evidence that it does not move at geological time scale, even though situated next to the turbulently convecting iron core, and being the hottest part of the convective mantle, and being a low velocity anomaly that is usually assumed buoyant, makes it a mechanical anomaly. We propose to designate it as the Trond" [Trond double prime] anomaly.

Since the discovery of the ultra-low velocity zones in the lowermost mantle, evidences for the presence of partial melt at the bottom of the mantle have continually accumulated. Melt is denser than solid at core mantle boundary pressures due to its higher compressibility. This removes the buoyancy threat and explains the low shear velocity. We suggest the centrifugal force as the mechanism for the stabilization of the Trond" anomaly.

Long-term stability of the Trond" anomaly creates the large-scale asymmetry in convective motions needed to explain the driving force for the systematic continental drift and the mechanisms of plume formation. We hope that thinking inertia will not negatively interfere with centrifugal inertia. Trond has the evidence. We, thanks to Alfred Wegener, have the mechanism. After all, our centrifugal forces only move the heavy melt not the solid continents. One can imagine that some form of channel or porosity waves flows at the core-mantle boundary towards the equatorial positions. The continents are only indirectly influenced by the weak centrifugal forces via patterning of the mantle convection, creating long wavelength asymmetries in basal drag and slab pull needed to explain large drift distances of the continents.

5.31 Escape tectonics and the extrusion of Alaska: Past, present, and future

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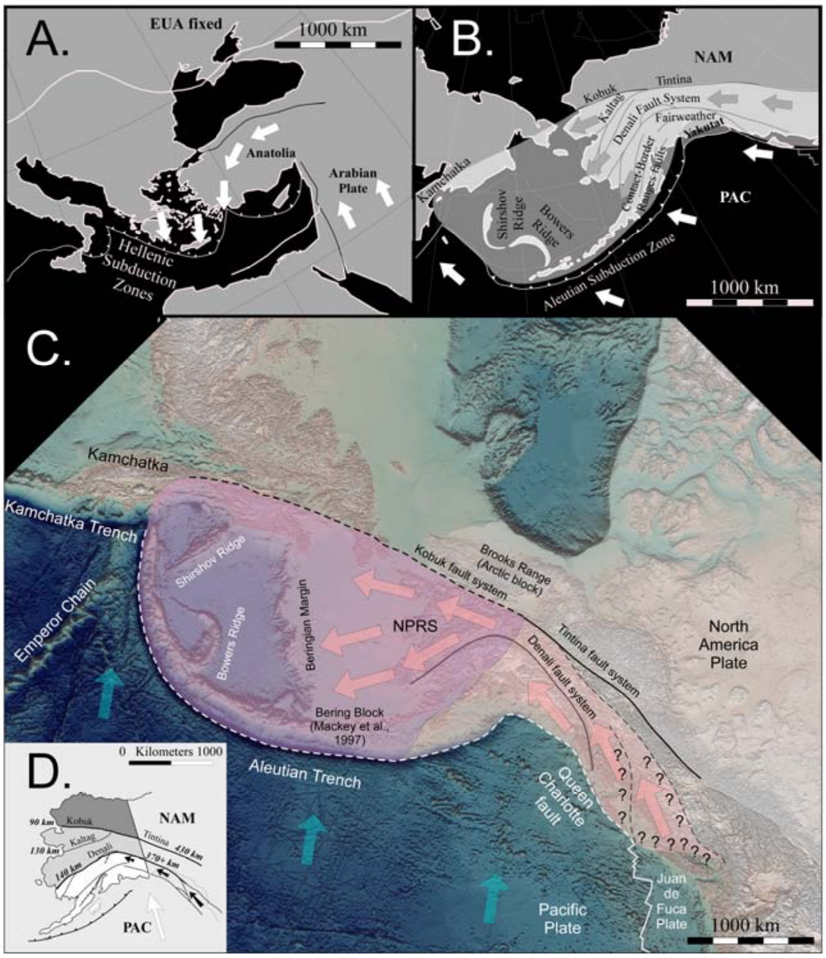
The north Pacific Rim is a tectonically active plate boundary zone, parts of which may be characterized as a laterally moving orogenic stream. Crustal blocks are transported along large-magnitude strike-slip faults in western Canada and central Alaska toward the Aleutian-Bering Sea subduction zones. Throughout much of the Cenozoic, at and west of its Alaskan nexus, the North Pacific Rim orogenic Stream (NPRS) has undergone tectonic escape. During transport, relatively rigid blocks acquired paleomagnetic rotations and fault-juxtaposed boundaries while flowing differentially through the system, from their original point of accretion and entrainment toward the free face defined by the Aleutian-Bering Sea subduction zones. Built upon classical terrane tectonics, the NPRS model provides a new framework with which to view the mobilistic nature of the western North American plate boundary zone.



5.32 Flavor of earliest Iapetus MORB, with local hot-spot influence, recorded through geochemical tracing of the Neoproterozoic Ottfjället dike swarm of the Middle Allochthon into the Scandian hinterland, Western Gneiss Region, Norway

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The Ottfjället swarm of Neoproterozoic mafic dikes, cutting Late Neoproterozoic sandstones, became a key, 30 years ago, to the tectonics of the Scandian Caledonides. Results of the present study show that their geochemistry reflects the composition of Neoproterozoic MORB generated during the earliest phase of opening of Iapetus at the Baltoscandian margin, with close parallels to the modern Mid-Atlantic Ridge.

The sandstones, with Vendian glacials, were deposited in basins related to opening of Iapetus, and the dikes intruded into distal parts of the Baltoscandian margin, close to the developing spreading center. Typical of the Särv Nappe in Sweden, and Sætra and equivalent nappes in Norway, they are keys due to contrast with similar sandstones lacking dikes at lower tectonic levels derived from inboard parts of Baltica. Thus, arguments were made for Scandian transport of the Middle Allochthon from far west of the present Norwegian coast.

The Ottfjället swarm was first recognized in Sweden, where the sandstones are locally 2 km thick, then traced to Norway with more deformation/metamorphism, but where dikes are still recognized, i.e. Oppdal, and Orkanger. It was suspected that other localities in the Western Gneiss Region in correct tectono-stratigraphic sequence, of highly deformed feldspathic quartzites with interlayered amphibolite, correlate with the Särv, even where tectonically thinned to 3-1 m, or where the 'dikes' are now eclogite. Near these are similar mafic 'dikes' intruding earlier metamorphosed Proterozoic basement rocks or 1190 Ma rapakivi granites of the Risberget Nappe with its mafic suite.

To test correlations, 123 samples of mafic rocks were analyzed for major and trace elements including REE, starting with dikes in quarries near Oppdal, then to more distal locations. With likely marginal contamination of major elements, discrimination was based on selected trace elements. Characteristics of mafic 'dikes' in quartzite, the Risberget Nappe and adjacent basement are shown and distinguished on three sets of diagrams: La_n/Sm_n vs. Nb/La, chondrite-normalized REE, and broad-spectrum element-discriminant diagrams. Typical samples from Oppdal and most of the Sætra Nappe and related rocks of this study (Oppdal Group) have La_n/Sm_n ratios 1.0 to 1.8, and Nb/La ratios 0.8 to 1.4. Most REE patterns are moderately LREE-enriched with no or very small Eu anomalies; a few are flatter. Despite these differences, all have near-parallel discriminant patterns, typically with small positive P anomalies, negative Zr-Hf anomalies and absence of negative Nb-Ta anomalies, showing no connection to arcs and no significant continental crust component. A subset of Sætra, Risberget, and basement dikes, the 'more alkaline' Ystland Group, is distinguished from the Oppdal Group by higher La_n/Sm_n, 1.8 to 2.5, but is otherwise similar. Divorced from Sætra-like compositions are chemically distinct gabbros and amphibolites in the Risberget Nappe, likely from Mesoproterozoic magmas intruded into the rapakivi granite. Mafic dikes in earlier deformed basement gneiss at Lepsøy, Midsund, and Geita are geochemically like those in the Sætra, implying this basement is in the far-traveled Middle Allochthon, different from parautochthonous basement of the Western Gneiss Region.

Geochemical data of this and earlier studies of the Ottfjället swarm, where NbSrY proxy values were used, are tightly grouped into MORB-like compositions (Oppdal) with moderate LREE enrichment north and south, and more LREE-enriched alkaline compositions (includingYstland) from northern Trondheimsfjord SE into Sweden. The alkali-rich composition stripe across the allochthon, even with carbonatite at two localities in its center, is at right angles to the dominant dike orientation in the best preserved locations. The stripe is also identical in width to regions of modern hot-spot influence near the Mid-Atlantic Ridge, thus giving a fleeting image of the development of earliest Iapetus oceanic crust.

5.33 Multiple antipodal remanence components in the Skye lava (UK): Complex thermal and chemical history and self-reversals

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Large Igneous Provinces, overwhelmingly of basaltic affinity are the surface expressions of catastrophically rapid dissipation of large quantities of internal heat. With an estimated volume of ca 10^7 km^3, the North Atlantic Igneous Province (NAIP) represents the third largest magmatic event on Earth for the last 150 Ma. The formation of the NAIP has been linked to the proto-Icelandic plume through paleogeographic reconstructions and geochemical observations. However, despite active research focus since the late 1980's, the temporal and physico-chemical ties between NAIP rocks, hotspot motion and continental break-up have not been demonstrated to fit a single regionally applicable and consistent geodynamic model. Therefore, in the framework of reinvestigating the paleomagnetic directions of the British Tertiary Igneous Province (BTIP), a sampling of ~200 cores (19 sites) in the lava pile of the Isle of Skye (Scotland) has been undertaken. Although 80% of the samples showed 'expected' behaviour with one or two components, three sites (20%) exhibits complex magnetization with up to five well constrained mostly antipodal components. This peculiar behaviour is only triggered trough careful stepwise thermal demagnetisation. Alternative field demagnetisation on companion core usually exhibits only two components. We are able to rule out acquisition of stray fields in laboratory equipment as an explanation and are left with an open question as to the origin of these multiple directionally opposed components. Variation in remanence stability under thermal and alternating field demagnetisation may reflect the combined action of two alteration processes, namely deuteric oxidation and regional alteration, which could have created secondary minerals that have the ability to self-reverse under specific conditions. It has been demonstrated for the Skye lava that regional hydrothermal activity widely occurs and that it can alter the magnetic properties of titanomagnetite in low deuteric oxidation states to such an extent that thermally stable magnetic phases with a single Tc above 500˚ may appear. The history of alteration of these lavas can be discussed as well as alternative explanations including multiple self-reversals, and other possibilities of episodic chemical or thermal remagnetisation.

5.34 Do newer granites heal older orogens?

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There has been much debate recently concerning the long-term (i.e., >1 m.y.) strength of continental lithosphere. In one model, dubbed jelly sandwich, the strength resides in the crust and mantle, while in another, dubbed crème brûlée, the mantle is weak and the strength is limited to the crust. (Burov & Watts 2006)

The fact that earthquakes in continental lithosphere tend to be concentrated in the crust has led to the suggestion that much of the long-term strength of the continental lithosphere resides in the crust (Jackson 2002). However, it has also been argued that the apparent considerable elastic thickness and plate-like behaviour of the continental lithosphere, as seen for example in flexural basins, requires the continental lithospheric mantle to have considerable strength (Burov & Watts 2006). Whilst Butler (2006) points out that the Himalayas perhaps exhibit both behaviours. This weakening of the continental lithospheric mantle is believed to be due to the presence of water (Maggi *et al.* 2000). Since the late-Archaean - early Proterozoic the creation of continental lithosphere within arcs would then be associated with the fluid fluxing and weakening of the mantle. Further 'Wilson Cycle' events would only exacerbate this situation. This then leaves us with the problem as to how any continental lithosphere could behave in a 'plate-like' manner. One such example is the Caledonides of Ireland, whose estimated elastic thickness is now in the order of 45km (Armstrong 1999). However, geologically these rocks comprise Ordovician to Silurian slate-belt volcaniclastic sequences formed during arc-continent collision, followed by subduction flip and subsequent suturing of Laurentia with Avalonia in the late-Silurian. They are, therefore, likely to have been underlain by a hydrated, and hence weak mantle. This contribution argues that the formation of post-orogenic granites during Acadian (mid-Devonian) transtension may have helped dehydrate and strengthen this lithosphere. The origin of these granites is a long standing problem. The presence of a normal Moho at about 30-35 km, plus the preservation of anchimetamorphic rocks at the surface argue against delamination models for granite genesis. The age of granite emplacement, some 20 Ma after suturing, argue against a subduction origin. However, the granite are associated with swarms of lamprophyric and appinitic dykes and Devonian pull-apart basins (Soper & Woodcock 2003). New numerical models demonstrate that decompression melting of a hydrated lithosphere to produce these lamprophyres during transtension would have advected sufficient heat into the base of a fertile crust to generate these granites. These models also imply the dehydration of the underlying mantle and subsequent post-orogenic strengthening of the continental lithosphere.

References

Armstrong, G., 1999, *Spatial variations in the flexural rigidity of the lithosphere in Ireland*. PhD thesis, National University of Ireland, Galway.

Burov E. B. and Watts, A. B., 2006, The long-term strength of continental lithosphere: "jelly sandwich" or "crème brûlée"? *GSA Today*, 16/1,4-10.

Butler, R.W.H., 2006, How weak are the continents?, *Geoscientist*, 16, 4-8.

Jackson, J., 2002, Strength of the continental lithosphere: Time to abandon the jelly sandwich?: *GSA Today*, 12/9, 4-10.

Maggi, A., Jackson, J.A., McKenzie, D., and Priestley, K., 2000, Earthquake focal depths, effective elastic thickness,and the strength of the continental lithosphere: *Geology*, 28, 495-498.

Soper N. J. Woodcock, N., 2003, The lost Lower Old Red Sandstone of England and Wales: record of post Iapetan flexure and Early Devonian transtension. *Geological Magazine* 140, 627-47.

5.35 TPW unplugged: Absolute plate motions and true polar wander in the absence of hotspot tracks

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Motion of continents relative to the Earth's spin axis may be due to either rotation of the entire Earth relative to its spin axis – true polar wander (TPW) – or due to motion of individual continents. Here we present a new method to separate between these for the last 320 My, based on the global average of continental motion and rotation through time in a paleomagnetic reference frame. Two main components are identified: a rather steady northward motion, and, during certain time intervals only, clockwise and counterclockwise rotations, which are interpreted as evidence for true polar wander (TPW). We find ~ 18^o counterclockwise rotation between ~ 250 and 220 Ma and the same of amount clockwise between ~ 195 and 145 Ma. The rotation axis is, in both cases, close to the reconstructed eruption site of the Central Atlantic Magmatic Province (CAMP) at about 200 Ma, which developed into the North American - South American - African triple junction. This is followed by further ~ 10^o clockwise rotation between ~ 145 and 135 Ma, followed again by the same amount of counterclockwise rotation between ~ 110 and 100 Ma, with a rotation axis further east, in the reconstructed area of North Africa / Arabia. These rotation axes mark the maxima of the degree two geoid during those time intervals, and the fact that the overall net rotation is nearly zero is an indication of long-term stability of the degree two geoid and related mantle structure. The latter of these two axes is quite close to the present-day centers of two Large Low Shear Velocity Provinces in the lowermost mantle, which is a further indication for their long-term stability. For the former, the location further west may reflect the contributions of geoid highs related to subduction at the western edge of Pangea, or be related to the CAMP plume. Cumulative TPW between late Carboniferous and the Neogene has been negligible, whereas continents have moved substantially north relative to the underlying mantle. Northward motion could be caused by mantle upwellings being stronger in the southern hemisphere, corresponding to an average northward component of mantle flow at shallow depths. We propose a new reference frame, mostly based on paleomagnetism, and corrected for the TPW identified in this study, that would be the most appropriate for relating surface to deep mantle processes between 320 and 130 Ma.

5.36 Large igneous provinces generated from the margins of the large low-velocity provinces in the deep mantle

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There is a clear correlation between downward projected large igneous province (LIP) eruption sites of the past 200 Myr and the margins of the large low-velocity provinces (LLVPs) at the base of the mantle. We established this correlation by using palaeomagnetic as well as fixed and moving hotspot reference frames. Our finding indicates that the majority of the LIPs have been generated by plumes that rose from the D" zone at the edges of the LLVPs. Most LIP eruption sites project radially downwards to the core–mantle boundary (CMB) within ±10º of the 1 per cent slow shear wave velocity contour in the SMEAN tomographic model. Steep shear wave velocity gradients have been mapped near the CMB along much of the lengths of the LLVP margins close to that contour which marks a faster/slower boundary (FSB) within the D" zone. The observation that eruption sites of LIPs as old as 200 Myr can be linked to this prominent present day seismic structure shows that the FSBs of the two LLVPs have occupied their current positions for at least as long and that the process that leads to the generation of deep-seated plumes has been localized on the FSBs at the margins of the African and Pacific LLVPs for the same interval. The persistence of the LLVPs over 200 Myr is consistent with independent evidence that they are compositionally distinct and are not just simply hotter than the material making up the rest of the D" zone.

5.37 An orocline that may have involved the entire crust

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Kazakhstan, located in the center of the Eurasian continent, is made of younger crust sandwiched between the old cratons of Siberia, Baltica and Tarim. A prominent geologic feature of Kazakhstan consists of two concentric horse-shoe shaped volcanic arcs, which are Devonian and late Paleozoic in age with the youngest arc on the inside, while subduction occurred in an outward directed pattern. Our recent paleomagnetic studies in the region show that in the Middle Devonian the arc, which is now strongly curved, was nearly straight and NW-SE trending. This arc marked the NE margin of the block that some have called Kazakhstania. The southern arm of the curved structure shows no significant changes in its relative orientation since the Middle Devonian, while its northern arm underwent ~ 180 degrees of rotation. Late Paleozoic paleomagnetic results constrain the rotations to the interval of about 390 Ma to 260 Ma or earlier.

Following S. W. Carey's original definition, the curved structures and their rotational history define the area as an orocline. Given what we know about the lack of décollement planes within the crust of this area, it seems reasonable to assume that the entire crust and possibly part of the upper mantle lithosphere was involved in the oroclinal bending. To our knowledge this is the first paleomagnetic confirmation of a lithospheric-scale stress-induced orocline, other than those caused by slab roll-back.

We consider that a potential geodynamic cause for this oroclinal bending may have been a dextral shear motion and a considerable clockwise rotation of Siberia, with respect to Baltica, Tarim, and the southern arm of the orocline. This movement of Siberia may have dragged the northern (Chingiz Range) end of Kazakhstania, while the collision of Tarim with Kazakhstania's southern corner (Tien Shan) created a back-stop. Continued subduction under the northern and southern limbs with an estimated subduction velocity of less than 1 cm/yr eventually led to closure of the intervening Balkhash-Ili ocean and tightening of the orocline. By the early Permian the Balhash-Ili represented a narrow oceanic basin with two subduction zones of opposite polarity, likely similar to the modern Molucca Sea subduction system.

5.38 Late Precambrian paleogeography of Baltica

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Global paleomagnetic data from the time between Rodinia formation and the dawn of the Phanerozoic still leave much to be resolved. In particular, the last part of this period contains disperse and partly contradictory results, providing ammunition to both adherents and non-believers of different global theories such as snowball Earth and true polar wander.

Despite valiant efforts to clear the horizons by Trond Torsvik and other lesser paleomagnetists, the picture remains incomplete also for his home continent of Baltica. A number of Sweconorwegian poles (c. 970-1100 Ma) indicate low to subtropical latitudes, while results from igneous rocks from SW Norway suggest high latitudes at c. 850-870 Ma. Russian and Norwegian sediment poles place the continent back at low latitude some time between 700 and 800 Ma, albeit these results are poorly dated.

For the Ediacaran, results are contradictory, with various studies giving both equatorial latitudes (Alnø complex), Intermediate latitudes (Winter coast sediments) and high latitudes (Egersund dykes). The situation remains confusing into the Cambrian, before a number of good and consistent results finally clear the mist in the Ordovician period.

The talk will discuss the available data, as well as some current work aimed at improving the data situation for the Ediacaran.

5.39 Adventures in the Bushveld Complex

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Despite the size of the Bushveld Complex and the wealth of its mineral deposits, it is perhaps surprising that it is so poorly characterised and understood, compared to other layered intrusions such as Stillwater, Skaergaard, Kiglapait, or Muskox, some of which are located in very remote terrain and not as well mineralized. Most research on the Bushveld Complex has been carried out on samples from the Eastern Lobe, where surface exposure is relatively good, and the Western Lobe, where extensive mining activity allows access to underground exposures. A great deal of effort has gone into characterization of the well-known mineralized horizons (Merensky Reef, UG-series chromitite layers, UZ magnetitites), but the vast thicknesses of magmatic cumulate rocks in the Bushveld Complex remain poorly studied. Perhaps most importantly, the origin and shape of the Bushveld Complex remains a mystery. What tectonic or magmatic events led to the production of more than 1 million cubic kilometers of basaltic magma 2 billion years ago?

In an effort to more fully characterize the Bushveld Complex gravity and magnetic models incorporating the full crustal thickness and lateral extent of the Bushveld Complex have been completed. These models have demonstrated the possibility that the Bushveld Complex could be connected at depth. However little physical property data existed prior to our modelling work, thus extensive physical property databases have been collected which have assisted with determining appropriate modelling parameters. This physical property data base has revealed unusual cyclicity in the density data, whereby the density increases upwards in a series of well defined layers, which may be related to emplacement mechanisms.

There are a number of strongly magnetised dykes that intrude the eastern Bushveld Complex. However, there are no well established dyke events at this time in southern Africa. Thus these dykes are likely to be close to the Bushveld Complex in age, with istotope systems have been partially reset. The palaeomagnetic pole position agrees well with recent determinations for the Bushveld Complex.

The large discrepancy between the narrowness of the isotopically determined age of the Bushveld Complex and the extensive polar wander path determined from early palaeomagnetic studies led to an extensive reinvestigation of the palaeomagnetic properties of the Bushveld Complex. These studies have resolved the discrepancy and provide a better defined pole for the Bushveld Complex. In addition a number of reversals have been identified, which will be further investigated throughout the Bushveld Complex as a whole.

5.40 Interactive Visualization and Monitoring of 3-D Mantle Convection

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With the imminent arrival of petascale computing in the United States by 2010, new strategies for visualizing and monitoring high-resolution numerical simulations on massively parallel computers are needed to overcome the extreme data and resource requirements. We have employed a visualization system consisting of 14 powerful Dell workstations, soon to be upgraded to Cell Processors each with a multi-terabyte disk system, connected via a high-speed network with a bandwidth on the order of a few gigabits per second to a locally situated massively parallel system with approximately 2,000 processing elements. This system has been constructed at the Laboratory of Computational Sciences and Engineering at the University of Minnesota. Near real-time interactive analysis of 3-D mantle convection at a rate of 1 to 2 frames per second, using around 10 million grid points has been carried out using a client-server application capable of streaming gigabytes of simulated data to a remote Powerwall with 13 million pixels.

Concurrently, we have constructed a web-portal that allows a user to monitor the same run at home or in a hotel room, using a laptop. In our case, interactive computing takes on the meaning of performing such special runs for a limited duration of time, say 1 to 2 hours. We can also rotate the visualized images within this time span. This calls for a balance between grid resolution and the number of processing elements required to provide the level of interactivity needed to achieve one to a few frames per second. Our mode of operation represents a new paradigm in numerical modeling that supports a trend toward both real-time visualization and monitoring of high-resolution models and a consequent reduction in storage of raw output data, since the interactive periods are by definition short, like a couple of hours. Using this interactive strategy periodically, we can facilitate long heroic runs extending over a few days on petascale systems.

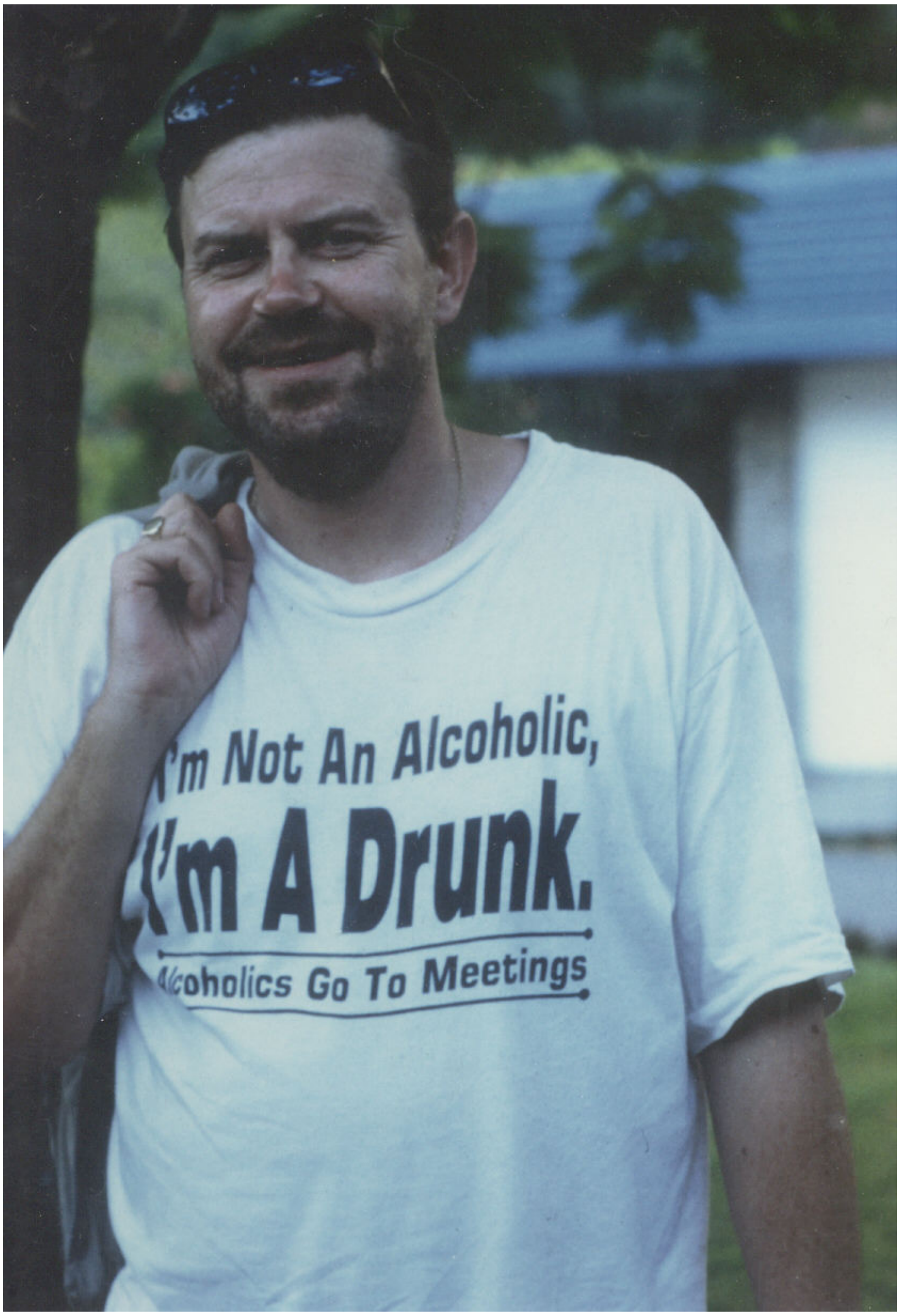
6 THE ORIGIN OF THE SPECIES

Torsvik is a wide-ranging, gregarious fauna. Especially prone to speciation, the genus has in its time successfully colonized a variety of habitats. Historically, taxonomists have tried to classify *Torsviks* in accordance with the ecological niches they occupy. However, this methodology has led to severe confusion, as all can be found belly up to the bar after midnight. Consequently, professionals are now attempting a provisional classification based upon behavioural categories.

Centerpiece Trond *(Torsvik plebus)*
This *Torsvik* is relatively easy to locate, and as such has been dubbed *Torsvik plebus*, the 'common, garden variety' species. Plumage is variable, but rumpled white shirts spotted with red wine are diagnostic. Both diurnal and nocturnal, *plebus* is characterized by convivial and extroverted decorum, mildly dishevelled grooming, consistent migration towards the center of attention, and a set of peculiar vocalizations including 'doodah,' 'Mickey Mouse,' and 'jpeg science.' It is an opportunistic feeder. Although *Torsvik plebii* can be easily displaced by some of the more aggressive species listed below, their high productivity and simplified diet ensure that they are able to rapidly reoccupy overgrazed habitat once the population of invaders has peaked. Common *Torsviks* are quite manageable in many respects, but have not yet been successfully domesticated.

Hangover Trond *(Torsvik dehydrus)*

Although semi-nocturnal, *Torsvik dehydrus* tends to favour the daylight hours. It is commonly sluggish until mid-afternoon, becoming most active as twilight approaches. Coherent vocalizations are uncommon, and its plumage is erratic. Other diagnostic traits include poor or incomplete grooming, red eyes, and vague utterances of pending reform. *Torsvik dehydrii* can on occasion be found in the calm backwaters that accompany the departure of houseguests. Characterized by very short individual life spans, *Torsvik dehydrii* populations follow boom and bust cycles typified by widely-spaced peaks. Professionals remain divided over critical aspects of *Torsvik dehydrus'* life cycle, particularly its reproductive habits. However, it is known that some individuals can remain in near-catatonic states for extended periods, perhaps helping explain their proclivity for surviving extended monsoons and other wet seasons.



Oriental Trond *(Torsvik asiaticus)*

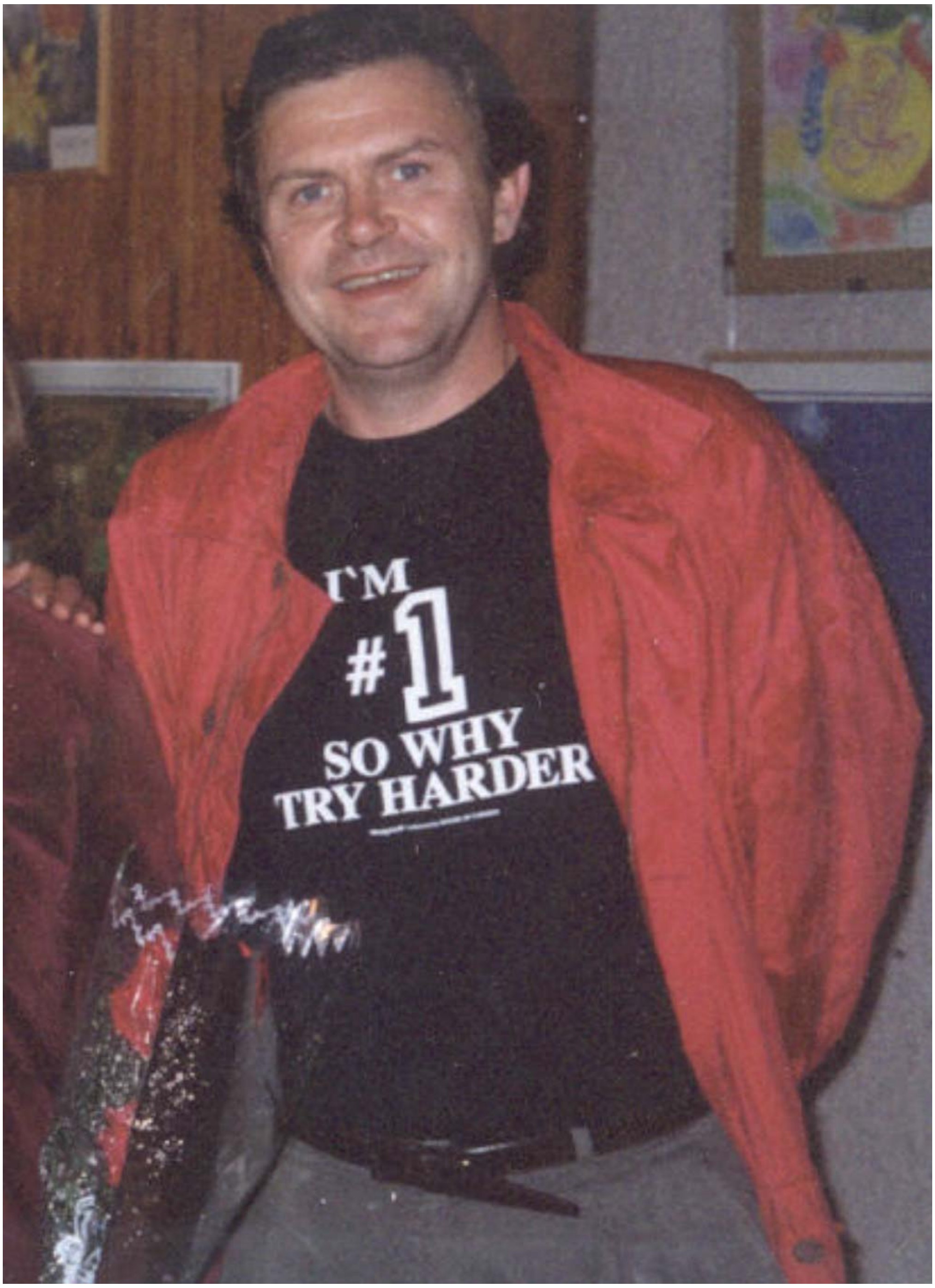
Whilst far-travelled, and thus seemingly well-adapted, this species occupies a narrow ecological niche. Although found throughout the Gondwanide continents, the self-imposed dietary restrictions that exclude all vegetable matter place severe limits upon *Torsvik asiaticus'* actual range. Conservative traits encourage rigid adherence to pre-programmed 'island hopping' migration paths, precluding adaptive radiation by consigning individual *asiaticii* to identical, non-challenging environments such as luxury hotels. *Torsvik asiaticus* is most easily identified by its affinity for imported whiskey and chicken tikka masala.

Immobilized Trond *(Torsvik immobilus)*

This is a rare and very dangerous *Torsvik*. Most commonly encountered in unfamiliar environments such as deserts or rain forests, *Torsvik immobilus* can react aggressively in the face of adversity, with unpredictable results. Diagnostic traits include long periods of sullen silence punctuated by intemperate vocalizations characterized by profanity. Closely related to *Torsvik asiaticus,* it is readily aggravated and easily provoked. *Torsvik immobilus* should be given the widest possible berth.

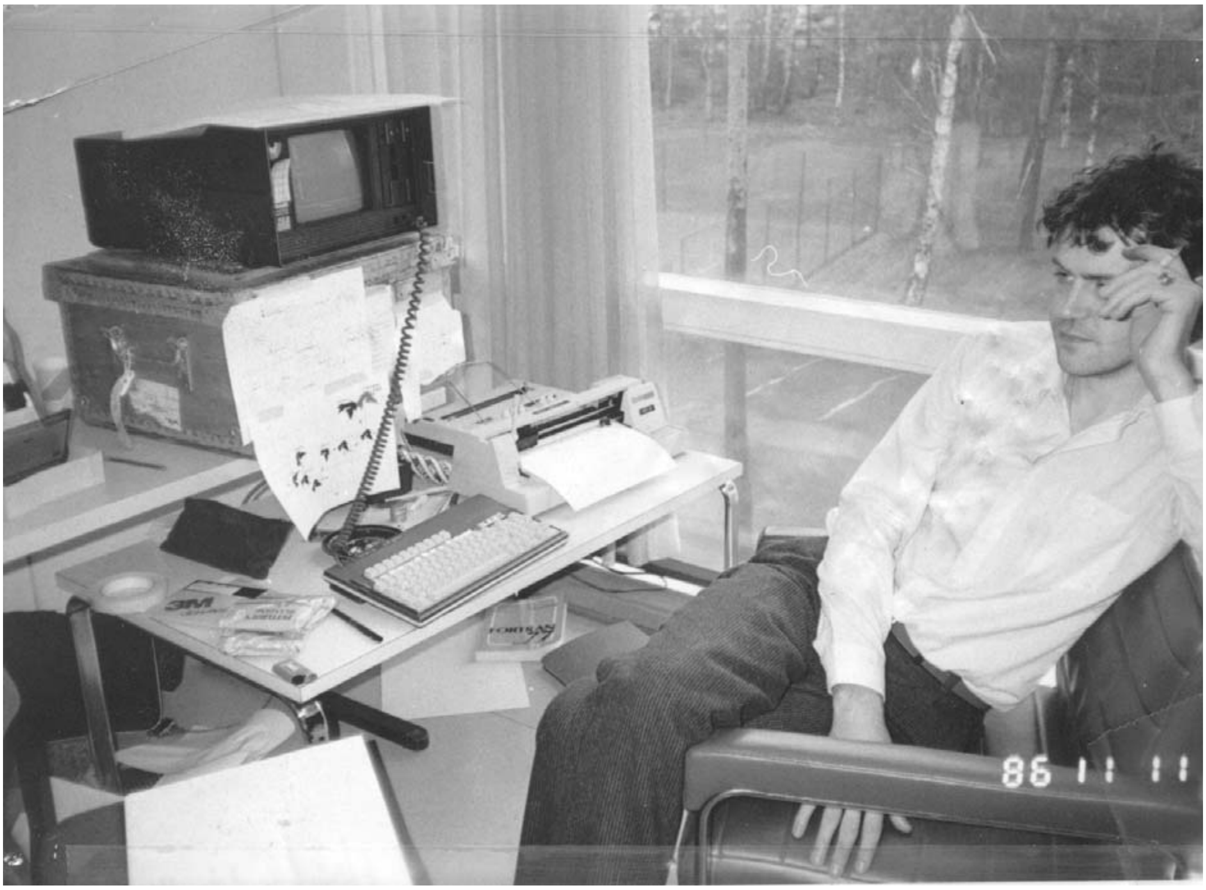
Number One Trond *(Torsvik primus)*

Commonly encountered in busy, social settings, this species is instantly recognized by a jet-black torso uniquely embellished with white filigree. *Torsvik primus* does not blend easily; rather, it will be found in the forefront of social gatherings at which it is present. If young ladies are in attendance, *Torsvik primus* may be observed indulging in a peculiar mating ritual accompanied by its unique vocalization, *'Hey, baybee, I'm a very famous scientist!'*



Primitive Trond *(Torsvik primitivus)*

An early, robust life-form, *Torsvik primitivus* was characterized by a ravenous appetite and an elevated metabolic rate. Almost exclusively nocturnal, it was most readily identified by its complete disregard for healthy physical activity, a high-cholesterol diet, intense periods of creative thought, and a fair degree of promiscuous activity. However, although blessed with a very high reproduction rate, *Torsvik primitivus* is now extinct. The species is known only through historical documents and the occasional trace fossil.



Voodoo Trond *(Torsvik monasticus,* subspecies *voodus)*

Although *Torsviks* in general tend to cultivate a scornful independence of the world around them, this evolutionary offshoot has developed a sense of respect. Consensus amongst the *cognoscenti* is that inbreeding amongst isolated communities of ancestral *Torsviks* resulted in the natural selection of a gene encouraging deference to a greater authority. (Whilst shared by all *Torsviks*, this particular gene is usually swamped by their *'Ego sum a Indoles'* basic reflex.) This example, *Torsvik monasticus voodus,* is known to conduct reverential inter-continental pilgrimages to Ann Arbor, Michigan. Such journeys are interpreted to constitute part of a genetically predestined search for enlightenment.

Domesticated Trond ***(Torsvik domesticus)***

Although rare, this outlier species has been the focus of intensive research and development. The most successful studies to date have relied principally upon fortune, as *Torsvik domesticus* usually appears without warning. However, current (competing) hypotheses suggest subtle trends may characterize its short life-cycle. One school of thought believes sightings tend to peak during the early phases of a study, with frequencies of appearance waning thereafter. Alternatively, a handful of modern scholars have suggested that, like fine wine, the best taste comes last.

Self-satisfied Trond *(Torsvik contentus)*

Relatively sedentary, *Torsvik contentus* will tenaciously colonize a local environment following (preferably short) migrations. Distinguishing characteristics include short attention spans, boisterous vocalizations, and proclivities towards Royal proclamations. These traits are most readily observed amongst juvenile populations. Although almost as common as *Torsvik plebus*, this species is of higher entropy and thus relatively unstable: high levels of environmental stress can engender mutation and rapid evolution towards life-forms resembling *Torsvik inebrius* (not shown).

Boring Trond *(Torsvik cavus)*
Plentiful in times past, this form of *Torsvik* is apparently on the decline. It is known largely from sequential series of trace fossils. Occurring as both molds and casts, they provide us with crucial documentation of the *cavus* life-cycle. However, few scholars consider it wholly extinct. Indeed, professional students of genus *Torsvik* anticipate its rediscovery, although most acknowledge that considerable mutation will by that time have rendered the original form completely unrecognisable.

Summary
Above, we have provided some simplified documentation of genus *Torsvik's* end-member species. Others ~ for example, *Torsvik inebrius, Torsvik magister rex,* or the celebrated *Torsvik agonistes* ~ tend to exhibit interim or transitional behaviour between these more distinctive organisms, and are consequently difficult to identify in the field. Indeed, some of the more curious offshoots are known to interbreed, and thus ought not to be classified as separate species.

Although *Torsviks* have been rigorously investigated by a cadre of dedicated scientists, their evolutionary origins remain obscure and their future uncertain. We hope that this brief catalogue will prove useful to future taxonomists seeking to better understand and conserve this amazing creature.

Sept. 21, 2007
The Sub-Committee

7 A WORD OF THANKS

This conference would not have been possible without the efforts of many people. On behalf of the sponsors NGU, Statoil, and PGP, the Organizing Committee would like to thank each and every participant ~ *sans* whom no meeting would have been possible at all.

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