Physics of Geological Processes (PGP): Some recent advances

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The last decade has seen a major change in the direction and focus of Earth Science research. Increased emphasis on quantitative aspects of geological processes has highlighted scientific problems requiring cross-disciplinary efforts for their solution. *Physics of Geological Processes* (PGP) is a cross-disciplinary center located at the University of Oslo. Its mission is to contribute to a more fundamental and quantitative understanding of the complex patterns and processes of the Earth ranging from the nanoscale structures of mineral surfaces to the movement of lithospheric plates.

Introduction

Earth science invariably starts with field observations, either directly with the naked eye, using some instrument, or indirectly - for example by the study of seismic waves after their propagation through a geological formation. However, the patterns observed in the field, whether they be fold structures, fracture patterns, topography, grain shapes etc. are usually highly complex. In fact, very few of the patterns we observe in the field are understood to the extent that we can formulate theories for their origin that take into consideration the forces and fluxes involved in their formation. Fortunately, complexity (even natural complexity) is not always a result of local particularities. Some patterns, in space or time, are not very sensitive to details and may be understood from more general principles. This is the goal of PGP: to identify and understand those patterns of the Earth that are not critically dependent on local details. Such patterns include many fracture patterns, the roughness of fractured surfaces, precipitation patterns such as natural travertines, many geomorphological patterns, patterns controlled by fluid migration, porosity evolution during compaction, wind- and wave generated patterns in unconsolidated materials, many weathering patterns, and a plethora of bio-patterns. And who knows: maybe life itself is such a pattern? If it is, then it is surely not unique to our mother Earth.

Understanding pattern-forming processes requires a multi-disciplinary approach. The search for the rules underlying natural patterns is most efficiently carried out in collaboration between those who know the patterns from nature (the field geologists) and those who know the rules for natural pattern formation (e.g. statistical physicists, applied mathematicians). In addition, one often needs to carry out physical experiments in that part of parameter space that nature has not itself explored. Thus the PGP strategy is to approach geological processes by integrated field-, experimental-, theoretical,- and computer modeling studies.

By the end of 2004, the PGP activity will represent about 40 man-years carried out by about 50 staff and students from 15 different nations. Two PGP staff members, professor Yuri Podladchikov and senior researcher Øyvind Hammer, were elected 'Outstanding Young Scientists' (YFF) by the Norwegian Research Council (NFR) in June 2004.

PGP is organized in three divisions: Geodynamics & deformation, fluid-rock systems, and interface-related processes. In addition to the research program, PGP is focusing on research relevance through interactions with the petroleum- and other industries, education, and communications with the public. PGP is currently starting 4 new projects on continental margin relevant processes funded by Statoil, Chevron-Texaco, and the *Petromax* program of the Norwegian Research Council. A separate Master program on the physics of geological processes was launched by the University of Oslo in 2004, and PGP is among the most media-covered research groups in Norway with about 25 exposures in Norwegian TV and radio since its start in February 2003, as well as numerous coverages in international media, including CNN, BBC, Der Spiegel, The Guardian, The Independent, The Economist, Al Arab etc.

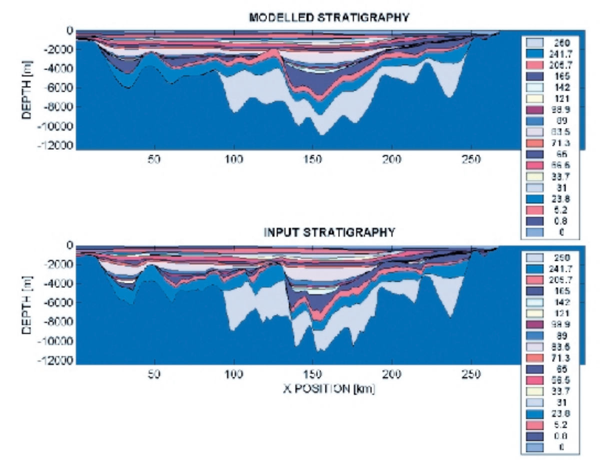

Fig. 1: The modeled stratigraphy (top) is generated by a numerical forward model and is similar to the stratigraphy interpreted from seismic data. Numbers in legend represent Myrs before present. Input stratigraphy is for the Viking Graben and was provided by Statoil.

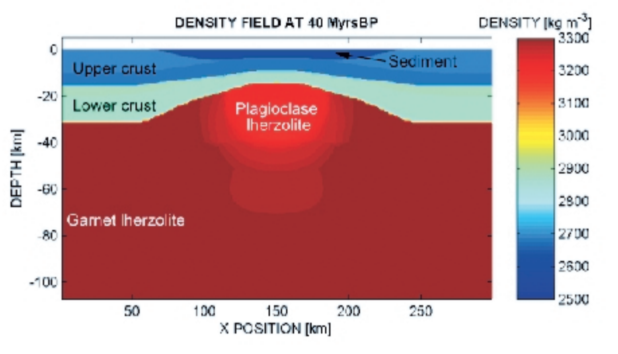

Fig. 2: Numerically calculated density field during lithospheric extension. Below the centre of the basin within the lithospheric mantle metamorphic reactions take place. Here, Garnet lherzolite transformed into plagioclase lherzolite because of pressure and temperature changes during the extension. Note, that in the above numerical simulation the sedimentary successions can be modeled with as high a resolution as shown in figure 1, which allows modeling both basin and lithospheric scale processes simultaneously.

In the following sections you will find a presentation of some recent PGP-research projects, with a bias towards continental margin relevant activities. Hopefully this will interest a broad audience - both among Earth scientists and a Geo-interested public.

Basin evolution: Effects of mineral phase transitions

Work at PGP addresses a variety of deformation processes on scales ranging from nanoscale structures formed by dissolution and precipitation on stressed mineral surfaces to the rotation of lithospheric plates. Here, we will focus on a project dealing with basin evolution and its coupling to mineral phase transitions.

Extensional sedimentary basins in general, and especially rifted continental margins, are major repositories of hydrocarbons. Hydrocarbon generation and maturation are controlled by the thermal evolution of the formations in which the organic material is located. Thermal history reconstructions of sedimentary basins are therefore essential for evaluating petroleum potentials. Furthermore, such reconstructions provide important insights into the geodynamic processes acting during lithospheric extension.

Most numerical models simulating extensional basin formation and deposition of sedimentary successions are based on kinematic stretching or thinning (e.g., McKenzie 1978; Royden & Keen 1980). In such models the velocity field controlling lithospheric extension is predefined by a set of stretching factors that determine the amount of stretching at every location in space and time. In these models basin subsidence is controlled by two main processes: first, stretching or thinning of the lithosphere where subsidence is caused by isostatic adjustment due to the replacement of lighter crustal material by heavier lithospheric mantle material (syn-rift subsidence), and second, thermal re-equilibration of the temperature field that has been perturbed during thinning of the lithosphere (post-rift or thermal subsidence). The thermal subsidence is driven by the densification of lithospheric rocks due to cooling during the thermal re-equilibration. The density of lithospheric rocks is assumed to change due to temperature variations alone.

However, the models described above commonly fail to reproduce observed sedimentary depositional histories, especially when constrained by the time interval given for the period of stretching, or the water depths assumed for specific time intervals. Although there are a variety of models that include additional parameters, such as independent mantle-thinning factors (i.e. depth-dependent thinning) or intra-plate stresses, to better reproduce observed sedimentary deposition, the main shortcoming of all these models is the absence of a physically and chemically realistic treatment of metamorphic reactions taking place within the lithosphere. Metamorphic reactions ('mineral phase transitions') cause density changes in the crust and in the lithospheric mantle during and after lithospheric extension (Petrini & Podladchikov 2000). The minerals and rock types generated by these transitions may, furthermore, have different material properties from the pre-existing ones, and may cause a weakening or strengthening of lithospheric rock units. This may cause either an increase or a decrease, respectively, of the basin subsidence rates.

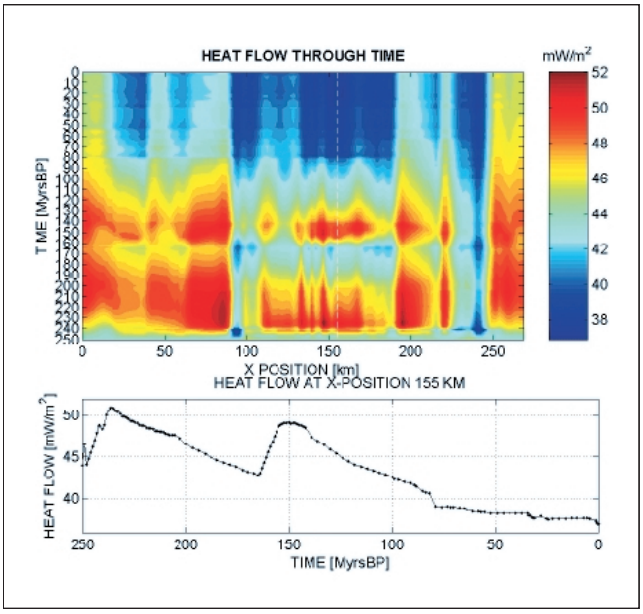

Fig. 3: Numerically calculated heat flow evolution at the base of the sediments through time and space. The heat flow data correspond to the numerically simulated stratigraphy shown in figure 1.

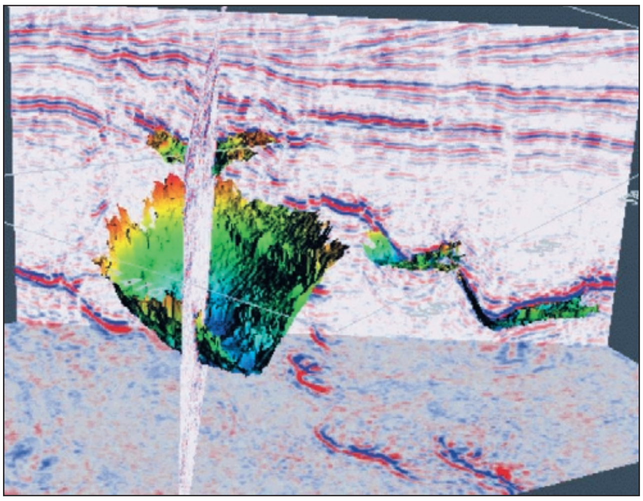

Fig. 4: A 3-D visualization of a saucer-shaped sill, as observed in seismic data from the Gleipne Saddle in the outer Vøring Basin. The sill appears as a high amplitude reflection, and is auto-tracked and plotted using VoxelVision software. The main saucer is 3 km by 4 km with approximately 500 m of elevation difference.

Our research focuses on developing numerical models which capture the essential physics of lithospheric extension and basin formation including metamorphic reactions. These models are then implemented in an inversion algorithm (Poplavskii et al. 2001), which enables reproduction of observed stratigraphies with the numerical models (Fig. 1). The forward models used to generate synthetic stratigraphies simulate both lithospheric and basin-scale processes simultaneously. Metamorphic reactions within the lithosphere are included within these models (Fig. 2) and the effects of metamorphic reactions on the basin formation processes and the resulting heat flow history (Fig. 3) can be studied and evaluated. Models for lithospheric extension including a realistic treatment of metamorphic reactions will improve our understanding of lithospheric extension and passive margin formation and provide more reliable reconstructions of the thermal history necessary for evaluating petroleum prospects.

Sill emplacement mechanism in sedimentary basins

Continental breakup is commonly associated with voluminous volcanic eruptions, as is the case for our North Atlantic margin where massive volcanic activity started around 62 Ma ago (Saunders et al. 1997). Some of this activity was associated with emplacement of voluminous sill bodies in hydrocarbon-bearing sedimentary rock units, and its effect on surrounding rock strata may have direct influence, on both the thermal maturation of organic material, and the permeability controlling hydrocarbon migration, both during and after sill injection.

Formation of saucer-shaped sills

The emplacement of sills (subhorizontal magma bodies) into sedimentary basins has a major impact on basin structure, permeability, and strength. When hot melt is intruded into the fluid-filled sediments, the surrounding sediments heat rapidly, pore fluids are expelled, and associated metamorphic reactions occur. The solidified sills and the associated structures represent permanent perturbations that will have a lasting influence on basin development. In particular, sill emplacement has important implications for petroleum prospectivity, because it may affect hydrocarbon production, migration, and trapping. Several prospective regions, such as the Vøring and Møre basins offshore Norway, are affected by sill emplacement

The geometric shape of sill intrusions is closely related to basin properties. In strongly structured basins, sills tend to follow lithological boundaries, pre-existing zones of weakness such as fault-planes, and adjust to a varying level of neutral buoyancy. However, in undeformed, unstructured basins, sill intrusions are typically saucer-shaped, with a width that increases with depth. The origin of the saucer shape has been debated, with no apparent consensus on a common theory. We have recently demonstrated that the saucer shape can be explained by a simple physical process: When the sill grows large compared to the thickness of the overburden, the deformation of the latter leads to a perturbation of the stress field close to the tip of the sill. This deflects

Fig. 5: A mosaic of aerial photographs of the Golden Valley sill, in Karoo, South Africa. The Golden Valley sill is a classic saucer-shaped intrusion with a flat-lying central part, and transgressive segments forming hills and ridges. The saucer is 19 km by 10 km, with up to 350 m of elevation difference.

the sill upwards towards the surface, generating a saucer shape (Malthe-Sørenssen et al. 2004).

Field observations of saucer-shaped sill geometries

Saucer-shaped sill complexes are frequently observed in unstructured sedimentary basins. Saucer-shaped intrusions typically have a flat, circular central region, terminated by inclined sheet segments that crosscut the sediments. We have recently mapped over 150.000 km of 2D seismic profiles and 3D seismic data in the Vøring and Møre basins. The style of the sill complexes varies significantly, with saucer-shaped intrusions dominating in undeformed basin segments. A typical example is shown in Figure 4, where the saucer shape is clearly observed. Seismic data also show that the width of the saucer increases with depth. Similar saucer-shaped structures dominate the terrain in the Karoo basin, South Africa, illustrated by the Golden Valley sill complex shown in Figure 5. The saucer shape is hence a common and striking feature of sill emplacement structures in undeformed basins.

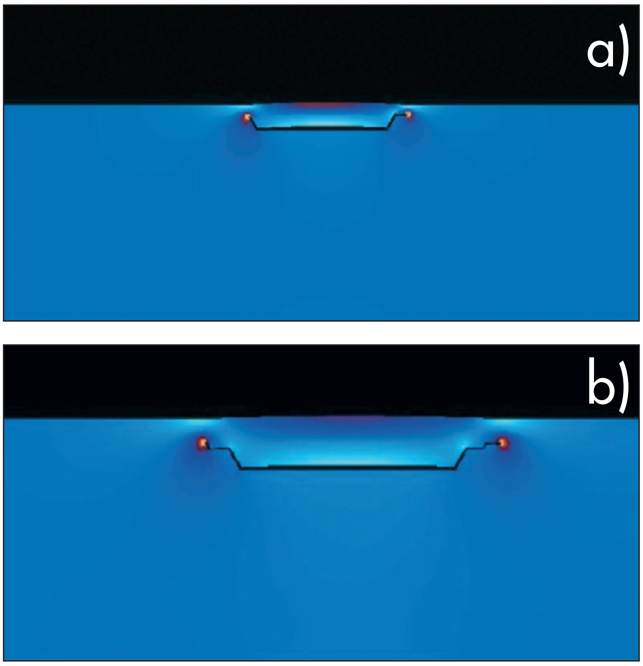

Fig. 6: Snapshots from simulations of sill emplacement in an unstructured basin. The sill was injected at 0.9 km (a), and 1.8 km (b) depth. Initially, the sill propagated horizontally, but it deflected upwards as the effect of the uplift of the overburden became important. The coloring indicates the tensile stresses in the host rock. Note that the thickness of the sill has been significantly increased to make it visible in the figure.

A numerical model for sill emplacement processes

The development of a quantitative understanding of sill emplacement and associated processes is still very much in its infancy. Most theoretical studies have concentrated on the two-dimensional shapes of dikes or sills (Pollard & Johnson 1973; Listen & Kerr 1991), and on the interplay between the viscous magma flow and fracturing. There is, for example, still no consistent theory that shows how sills form from dike swarms, and how sills and dikes interact to form intrusion complexes.

We address the sill emplacement process by a coupled model: The host rock is modeled as an elastic material using a discrete element model, and the interaction of magma and wall rock is modeled through a pressure affecting the host rock along the sill boundaries. During a simulation, the pressure is increased gradually. A discrete element model is used to model the elastic deformation and fracturing of the surrounding host rock. The equilibrium configuration of the sill is found for the prescribed pressure, and the sill propagates as a fracture if the stress exceeds the failure criterion at the tip of the sill. The pressure is then further increased, and the process continues.

This model is simple, but contains the necessary physical mechanisms to address sill emplacement

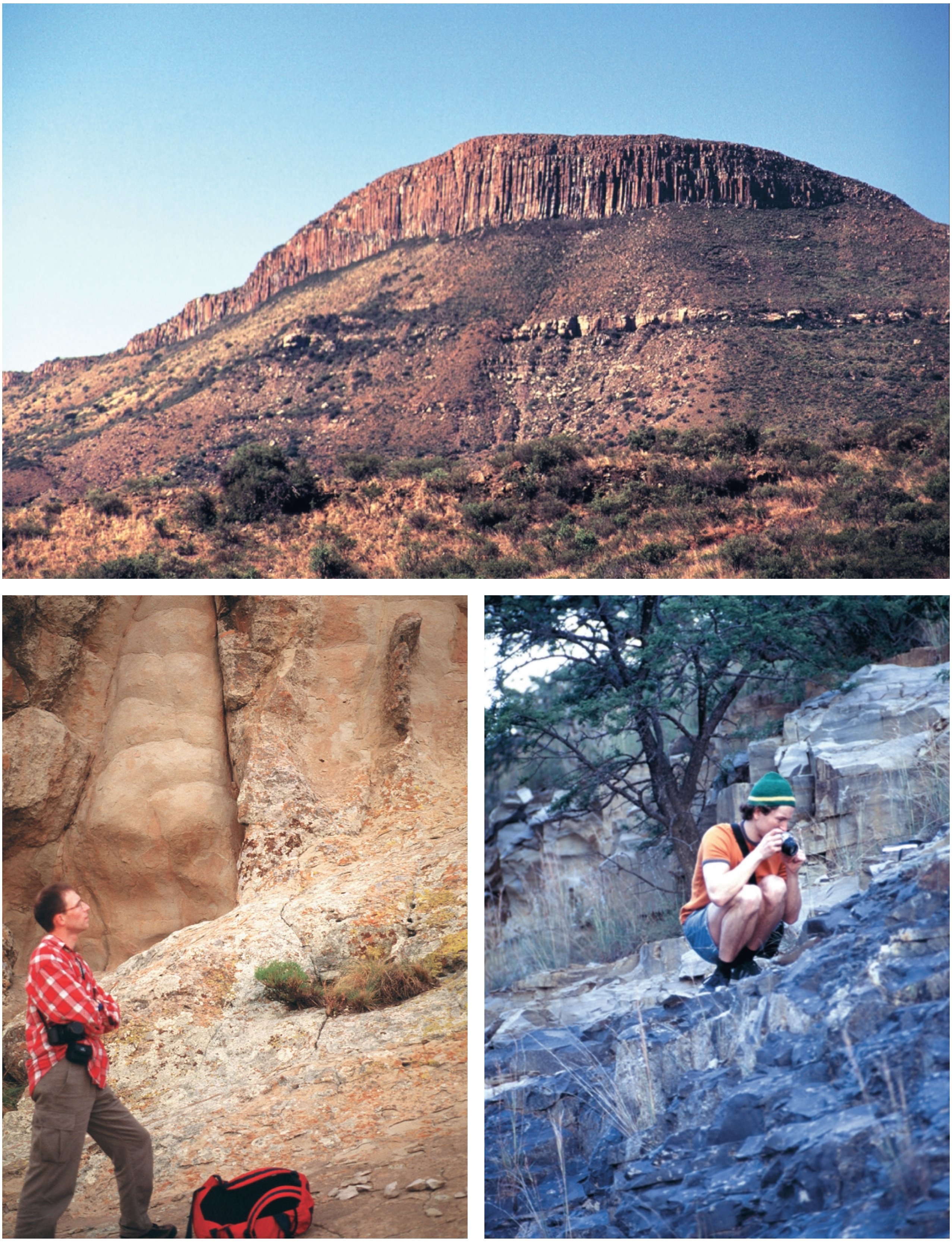

Fig. 7: Field studies of contact metamorphism and hydrothermal vent complex formation were carried out in the Karoo sedimentary basin, South Africa. Upper figure shows about 200 meter thick sill intruding horizontally layered Karoo sandstones and mudstones. Bottom right figure: Vent expert Henrik Svensen studying contact metamorphism in mudstones above a sill intrusion in Southeastern Karoo, Bottom left: Physicist in the field, Anders Malthe-Sørenssen, studies fluidized sandstone dikes and other features in hydrothermal vent complex in the Stormberg group. (photos: Bjørn Jamtveit/PGP)

Fig. 8. The AMASE-2003 crew in Bockfjord on a sunny day in August 2003. The mountain in the background is Sverrefjell, a Quaternary volcano. Expedition participants from left to right: Vittorio Bernardini (EMGS), Aldo Ambrosio (EMGS), Tori Hoehler (NASA), Øyvind Hammer (PGP and the Natural History Museum in Oslo), Andrew Steel (Carnegie Institution of Washington), Jennifer Heldman (NASA), Ellen Karin Mælum (PGP's expedition artist), Liane Benning (University of Leeds), Dag Dysthe (PGP), Hans Amundsen (PGP, expedition leader), Jens Feder (PGP-director), Maia Schweizer (Carnegie Institution of Washington), Kirsti Moe (NRK, Schrödingers katt), Nobel laureate Ivar Giæver (head of PGP-Board), Allan Treiman (Lunar and Planetary Institute), Bjørn Jamtveit (PGP co-dircetor) and Frank Bjarkø (NRK, Schrödingers katt). (photo: Kjell Ove Storvik/PGP).

processes. In particular, the model allows us to identify the mechanisms responsible for a specific effect. A unique strength of the model is that the path of the sill is not pre-defined, but is determined by the dynamics of the emplacement process. Simulations with varying initial depths are illustrated in Figure 6.

Saucer shape is a magma-tectonic effect

The coupled model for sill emplacement reproduces the saucer shape observed in field and seismic data, and the model allows us to study the mechanisms responsible for deflection of the sill. Modeling shows that the sill emplacement process can be divided into two phases: In the initial phase, the sill is short, and the stress field around it is not significantly perturbed by the free surface above the sill. When the sill reaches a particular width, typically 2-3 times the overburden thickness, the shape of the sill and the stress field around it become significantly perturbed by the asymmetry of the boundary conditions: It is easier to deflect the overlying strata than to deform the host rock underneath. As a result, the stress field becomes asymmetric, leading to a deflection of the sill. The asymmetry in stresses leading to the formation of saucer-shaped sills is therefore induced by the sill itself, and is not due to pre-existing structure or stresses in the basin.

Hydrothermal vent complexes

PGP-associated researchers have spent about 5 years working on the characterization and understanding of hydrothermal vent structures in volcanic sedimentary basins. The study was initially motivated by seismic interpretations suggesting that pipe-like structures emanating from sill intrusions were common in the sedimentary basins off the Norwegian coast. The project 'petroleum implications of sill intrusions' was supported by many of the petroleum companies operating on the Norwegian shelf. Initially, the project mainly focused on the mechanisms of sill emplacement and the associated expulsion of pore fluids from surrounding sedimentary strata (Malthe-Sørenssen et al. 2004; Jamtveit et al. 2004; Svensen et al. in prep). Extensive field work was carried out in the Karoo sedimentary basin in South Africa where intrusive sills occur abundantly in a basin that covers half of South Africa and where hydrothermal vent structures form at various stratigraphic levels (Fig. 7). It eventually became clear, however, that the total volume of pore-fluids expelled from the sedimentary rocks following sill emplacement in large igneous provinces is indeed huge. On the mid-Norwegian margin, a large sill complex intruded shale-dominated lithologies about 55 Ma ago. Order-of-magnitude estimates of the flux of greenhouse gases prompted by the sill emplacement immediately suggested that we had found a solution to the Eocene global warming enigma. The results of this study were published as the cover story of *Nature* on June 3rd this year (Svensen et al. 2004), and extensions of this project to other regions and other large scale climatic events have already been funded and initiated.

'AMASE'

During the last two field seasons PGP has arranged cross-disciplinary geology-biology-physics fieldtrips to Bockfjorden on NW Spitsbergen. The *Arctic Mars*

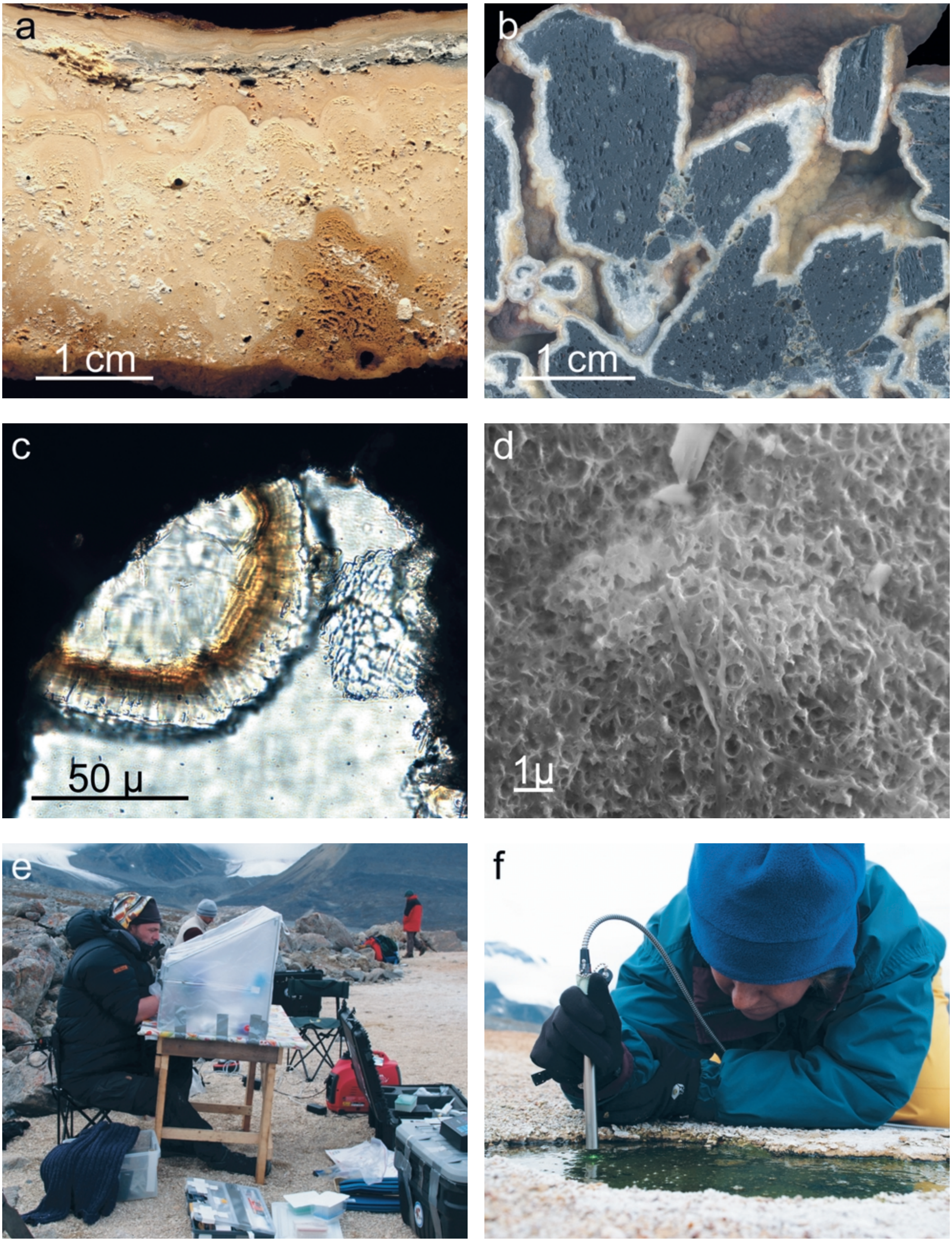

Fig. 9. (a) Stromatolite textured magnesite deposit from Sverrefjell lava conduit; (b) Magnesite cemented lava breccia; (c) Magnesite-dolomite globule inside lava vesicle; (d) SEM image of organic material coating lava vesicle; (e) In-field characterization of genetic signatures of microbial cells using PCR (Polymerase Chain Reaction). Courtesy of Carnegie Institution of Washington (photo: Kjell Ove Storvik/PGP); (f) In-field detection of organic material using laser fluorescence techniques. Courtesy of NASA - Jet Propulsion Laboratories (photo: Kjell Ove Storvik/PGP).

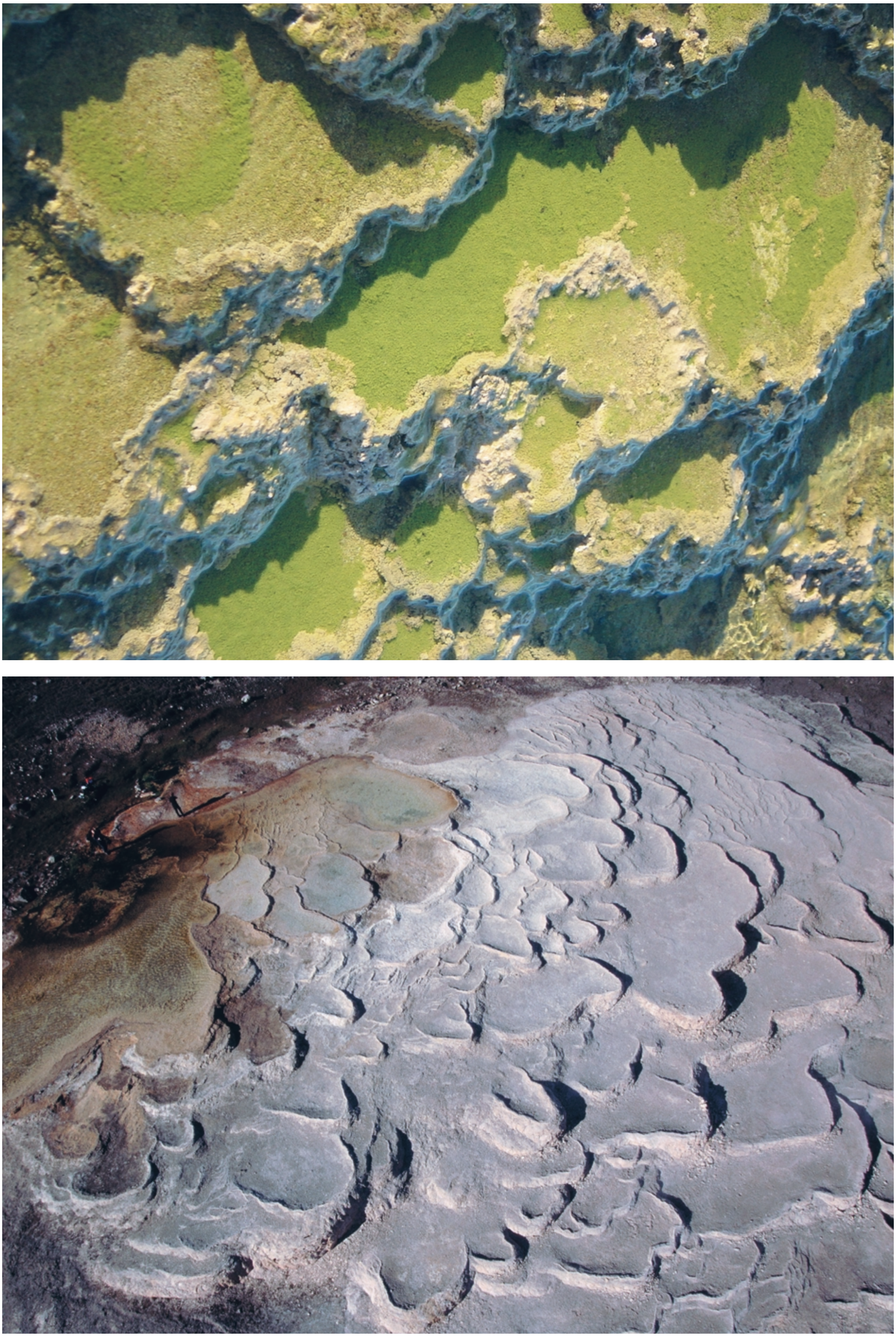

Fig. 10. Left: Aerial photograph of the Troll travertine system, about 100 m across. Main spring in the upper left corner. Lower terraces are currently dry. (photo: Kjell Ove Storvik/PGP). Right: Bio-activity in the travertine terraces is obvious and has significant effects on the water chemistry. Its role in the travertine pattern-forming processes is however not clear (photo: Tori Hoehler/NASA).

Analog Svalbard Expedition (AMASE) is a collaborative effort including among others NASA-JPL, the Carnegie Institution of Washington (CIW), the University of Leeds, and Pennsylvania State University (Fig. 8). The project studies pattern-forming processes in hot spring environments and the role of biogenic processes during precipitation and weathering of carbonates in Mars analog environments on NW Spitsbergen. Carbonate deposits in the Quaternary Bockfjorden volcanic complex (BVC, Skjelkvale et al. 1987) include calcite deposits (travertine) associated with hot springs, stromatolite textured magnesite in lava conduits (Fig. 9a) magnesite cemented lava breccias (Fig. 9b) and ubiquitous magnesite-dolomite globules inside lava vesicles (Fig. 9c). The carbonate globules were first described by Amundsen (1987) and are the only known terrestrial analog to carbonate globules in the Martian meteorite ALH84001 (Treiman et al. 2002). AMASE also involves development and testing of instruments (Fig. 9e, f) aimed at future 'Search for Life' missions to Mars, in cooperation with CIW and NASA-JPL (Steele et al. 2004).

Studies of the volcano-hosted carbonate deposits involve geochemical and microbial studies including a detailed inventory of organic compounds present within the volcanic rocks. Initial studies concluded that the BVC carbonate globules formed due to low temperature hydrothermal activity (Treiman et al. 2002) and recent work has shown that BVC carbonates are associated with organic material and microbial cells (Amundsen et al. 2004). Preliminary data (courtesy of G. Cody, CIW) suggest both abiotic and biotic origins for organic matter in the volcanic rocks. Possible roles of microbial activity during carbonate deposition remain to be established.

Results from AMASE 2003 and 2004 have spurred increasing interest for using Svalbard and BVC as testing grounds to develop concepts for `Search for Life` missions to Mars. AMASE 2004 involved the first ever field test of a suite of instruments capable of detecting microbial activity on Mars. Future work, in collaboration with CIW, NASA-JPL and other institutions, will focus on the detection of biosignatures and their preservation in Mars analog arctic environments and involve further field testing of portable instruments being developed for future Mars missions.

Travertine patterns

The main goal of the travertine project is to obtain a quantitative understanding of the formation of the terrace structures forming around the Troll and Jotun springs, located along a fault on the western shore of Bockfjorden (Fig. 10). The Troll and Jotun springs are probably the northernmost documented hot springs on land and precipitate calcite downstream from the main spring outlets. Stable isotope data (Hammer et al. in press) indicate that the main fluid source is glacial melting and that the carbon source is likely to be local marble.

Computer models, including coupled fluid flow and carbonate precipitation, produce terrace-like patterns, but the detailed role of all the processes involved is not yet resolved.

Abundant microbial activity is evident both in the hot spring pools and as endolithic communities residing within rocks in dry travertine terraces. Detailed studies of the fluid composition of the springs and its evolution during travertine precipitation demonstrate furthermore bio-effects on the fluid chemistry. However, a direct link between microbial activity, carbonate deposition and the formation of the travertine patterns has yet to be established.

Final remarks

Norway's location, healthy economy and focus on 'Earth-related systems' give our country a competitive advantage in Earth Science-related research. Norwegian geological research has traditionally been very prominent on the international stage since the beginning of the last century when the work of V.M. Goldschmidt and W.C. Brøgger on both basic and applied aspects of the geosciences made Norway not only an internationally leading nation in the Geological Sciences, but also made its geoscience very visible and relevant for the Norwegian public. The relative strength and relevance of Earth Science in Norway is reflected by the fact that 4 out of the first 13 Norwegian Centers of Excellence are within basic or applied geosciences. This represents a golden opportunity to capitalize on this competitive advantage in the Earth Sciences.

The last decade saw major changes in the focus of the Earth Sciences. It became clear that the patterns observed at the surface of our planet are in many cases not only a result of interlinked geological processes, but also of the coupling between processes taking place near the surface of the geosphere and those of the biosphere, hydrosphere and atmosphere. This coupling is particularly important for the relevance of the Earth Sciences to society since many challenges are related to energy and environmental issues intimately connected to processes taking place at the 'top of the geosphere'.

The coming decades will see dramatic progress in our understanding of dynamic processes on both Earth and other planets in our solar system. The recent discovery of shallow seas, and a likely atmosphere on early Mars highlights the relevance of obtaining a fundamental understanding of pattern-forming processes on the surface of the Earth as a basis for planetary exploration projects.

Today, PGP's focus is clearly on endogenic geologic processes: deformation, fluid migration, and growth and dissolution processes. Yet, the effects of the processes of the deeper Earth on the thermal evolution of sedimentary basins and on the composition of the atmosphere have repeatedly connected us to the exogenic realm and to the geosphere's impact on fossil fuel, climate, and the biosphere. Through our collaboration with NASA researchers (see 'AMASE' section above) and researchers connected to the 'earth systems science division' of the Worldwide Universities Network (WUN) (where the Universities of Oslo and Bergen recently became members), PGP is currently seeing a continuous expansion of our 'surface-patterns' activities with applications both to the Earth and other planets in our solar system.

In the future, it will be a challenge both for PGP and for any other research environment that engage in exogenic geological processes, to make an adequate connection between the Earth and Life sciences. A liaison where the focus is on the mutual interaction between the organic and the inorganic world rather than on rational ways of apportioning the geological field to mineral collectors on the one hand and fossil hunters on the other. Again, cross-disciplinary activity will be imperative.

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