

Sonja L. Philipp and Valerio Acocella (Eds.)  
**Rock Fractures in Geological Processes**

Abstracts of the Presentations of the Symposium,  
London, 26–27 November 2013



Universitätsdrucke Göttingen



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# TECTOR

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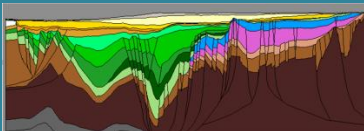
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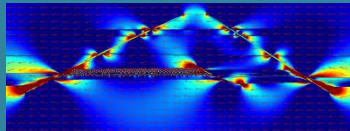
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## CONTENTS

Preface	9
<b>On the jubilee Ágúst Guðmundsson</b> <i>S.L. Philipp</i>	11
<b>Fractures, Faults, and Rock Properties</b>	17
Models of fracture lineaments – joint swarms, fracture corridors and faults in tight rocks, and their genetic relations <i>R.H. Gabrielsen &amp; A. Braathen</i>	19
Fluid overpressure of quartz mineral veins in the South Wales coalfield: implication for mechanism of fracture formation in foreland basins <i>T. Fukunari &amp; A. Gudmundsson</i>	25
Effects of facies and diagenesis on fracture propagation and reservoir permeability in limestone-marl alternations <i>F. Afsar, H. Westphal &amp; S.L. Philipp</i>	27
Sub-horizontal faults in clayey layers: macro- and microstructures <i>C. Homberg, N. Lemonnier, V. Roche, M. Rocher, A. Boullier</i>	33
Characterization of fault zones in Triassic Muschelkalk limestones of the Upper Rhine Graben with regard to geothermal exploration <i>S. Meier, J.F. Bauer &amp; S.L. Philipp</i>	37
Infrastructure and mechanical properties of a normal fault zone in Bunter sandstone (Lower Triassic) in the Upper Rhine Graben <i>J.F. Bauer, S. Meier &amp; S.L. Philipp</i>	41
Applicability of failure criteria and empirical relations of mechanical rock properties from outcrop analogue samples for wellbore stability analyses <i>D. Reyer &amp; S.L. Philipp</i>	45

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<b>Volcanotectonics</b>	<b>49</b>
Shallow magma chamber formation and evolution <i>Z. Barnett &amp; A. Gudmundsson</i>	<b>51</b>
Rock fracture as a precursor to volcanic eruptions <i>C. Kilburn</i>	<b>53</b>
Influence of previous structures in shallow feeder dyke-eruptive fissures propagation <i>I. Galindo, L. Becerril &amp; M. Romero</i>	<b>55</b>
Magma and tectonics along divergent plate boundaries: insights from field and modelling data <i>V. Acocella, D. Trippanera, J. Ruch, B. Abebe, T. Thordarson &amp; G. Norini</i>	<b>59</b>
The formation and role of caldera ring faults <i>J. Browning &amp; A. Gudmundsson</i>	<b>61</b>
Three-dimensional geometry of Las Cañadas caldera phonolitic dykes <i>S. Aragón, A. Geyer, J. Martí &amp; G. Aguirre-Díaz</i>	<b>65</b>
The effect of sill emplacement on petroleum systems <i>I.F. Løtveit, A. Gudmundsson &amp; M. Sydnes</i>	<b>67</b>

## **Preface**

Rock fractures play a major role in many geological processes, such as plate tectonics, earthquakes, volcanic eruptions and fluid transport in the Earth's crust. The present volume contains the abstracts of all presentations of the symposium „Rock Fractures in Geological Processes“, held on 26-27 November 2013 in London, honouring the 60th birthday of Ágúst Guðmundsson, chair in Structural Geology, Royal Holloway University of London, a leading expert in the field and author of a well known text book of the same title.

The symposium covers all topics related to fractures in the Earth's crust, e.g., crustal stresses, rock mechanical properties, field analysis of fractures – from joints and faults to mineral veins and dykes -, analytical, analogue and numerical models of fractures and related fluid transport, as well as the activity of faults and volcanoes including calderas, and economic aspects such as exploration and exploitation of hydrocarbons and geothermal energy. As the symposium starts with a laudation, the first text of this volume briefly introduces the jubilee and his research.

The symposium continues with two series of talks, their abstracts presented in the following. The first part contains seven contributions on faults, fractures, and rock properties. First, Roy Gabrielsen and Alvar Braathen present a model for the classification and development of fracture lineaments from joint swarms, via fracture corridors to faults. In the next contribution Tetsuzo Fukunari focuses on mechanisms of fracture formation in foreland basins based on field studies of quartz mineral veins in the South Wales coalfield. Filiz Afşar et al. present a study on joints in the Blue Lias of the Bristol Channel, combining methods of sedimentology and structural geology to analyse the effects of facies and diagenesis on fracture propagation in limestone-marl alternations. Catherine Homberg et al. then investigate macro- and micro- structures of sub-horizontal faults in multi-layered clay/limestone systems in Southern France. Silke Meier et al. characterize fault

zones in outcrop analogues of the Triassic Muschelkalk for geothermal exploration in the Upper Rhine Graben. Johanna Bauer et al. then present a detailed study on one normal fault zone in the Triassic Bunter sandstone, also a geothermal reservoir rock of the Upper Rhine Graben. The first part ends with a presentation by Dorothea Reyer and Sonja Philipp on the applicability of failure criteria and empirical relations of mechanical rock properties from outcrop analogue samples from the North German Basin, with importance for geothermal drilling and hydraulic fracture stimulation.

The second part of contributions is on volcanotectonics. First, Zoe Barnett presents numerical models on the formation and evolution of shallow magma chambers. Then Christopher Kilburn comments on models using rock fractures as a precursor to volcanic eruptions. The effect of previous structures in shallow feeder dykes on the propagation of eruptive fissures is then elucidated by Inés Galindo et al., using field examples from the Canary islands and numerical models. Valerio Acocella et al. then discuss magma and tectonics along divergent plate boundaries, presenting insights from field data from Iceland and the Main Ethiopian Rift as well as analogue models. John Browning et al. present a study on the formation and role of caldera ring faults, using a field example from Iceland, analytical and numerical models. This is followed by Arago et al. analysing the three-dimensional geometry of the Las Canadas caldera, Tenerife. The final presentation, given by Ingrid Fjeldskaar Løvteit et al. bridges the topic of volcanotectonics back to general presentations on fractures, focussing on the effects of sill emplacement on petroleum systems.

We wish all participants of the symposium an enjoyable meeting with interesting contributions and fruitful discussions, all readers of this abstract volume beneficial inspiration and Ágúst a happy birthday!

*Sonja Leonie Philipp*  
*Valerio Acocella*

## On the jubilee **Ágúst Guðmundsson**

*Sonja Leonie Philipp*



Ágúst Guðmundsson holds a University of London Chair in Structural Geology at Royal Holloway and is a leading expert in research on rock fractures. This symposium is held to mark his 60th birthday. In the following text I briefly review his biography and scientific contributions.

**Ágúst Guðmundsson (2011)**

## Name

The Icelandic letter Á is pronounced as „au“ in German, or the „ou“ in house, ú as „oo“ in too, or the German u-sound. In fact, in contrast to many others, for Germans it's very easy to pronounce the name Ágúst correctly as the name August exists in German. However, it seems impossible for anyone not with Icelandic mother tongue to pronounce „Guðmundsson“ correctly (something like „Gwðmundsson“, the ð being a voiced fricative similar to the „th“ in the). But this does not really matter much since, as is normal usage in Iceland, Guðmundsson is not a family name, but a patronym. This means his father's first name was Guðmundur, therefore he is Guðmund(ur)'s son. He says himself: „My name is Ágúst, and I am Guðmunds' son“. This is why I will write only Ágúst in the following, not Gudmundsson as would be more common for Non-Icelanders.

## Childhood and Education

Ágúst was born on November 26th 1953 in Reykjavík, the capital of Iceland, and grew up in Kópavogur, in the suburbs of Reykjavík. He studied general geology at the University of Iceland, Reykjavik, and worked as a part-time teacher at the Sund Junior College (geology, astronomy, computer science, and mathematics). He received a Bachelor of Science degree in 1977, and a B.Sc. Honours in tectonophysics in 1978 and worked as a field geologist for the National Energy Authority (Orkustofnun) in Iceland. He continued his studies at Imperial College London, where he obtained an M.Sc. in structural geology and rock mechanics with a thesis entitled “Tectonics of the Reykjanes Peninsula, Southwest Iceland” in 1979. Then he returned to Iceland, worked fulltime as a teacher at the Sund Junior College and at the same time was an external PhD student in tectonophysics at the University of London. In 1984 he finished his PhD with a thesis entitled “A Study of Dykes, Fissures, and Faults in Selected Areas of Iceland”. Both his MSc and PhD theses were supervised by Professor Neville J. Price.

## Professional Appointments and Awards

In 1985 Ágúst started as a research scientist at the Nordic Volcanological Institute, University of Iceland and soon, in 1987, became a research professor there. He was President of the Geoscience Society of Iceland 1994-1996. In 1997 Ágúst was elected to the Iceland Academy of Sciences (Visindafelag Íslendinga). In that time he also enjoyed appointments as visiting professors in volcanotectonics at the Institute of Earth Sciences, Jaume Almera, Barcelona, and in tectonophysics at the University Pierre et Marie Curie, Paris.

From 1998 Ágúst was a research professor, and from October 2000 a full professor (a Chair), in hydrogeology of solid rocks at the Geological Institute of the

University of Bergen, Norway, where I joined his group as a doctor student in early 2001. In 2002 he was elected to Academia Europaea (the European Academy of Sciences, Humanities and Letters). From 2003-2007 Ágúst was Chair of structural geology and geodynamics and Head of Department at the Geoscience Centre of the Georg-August-University of Göttingen, Germany. In February 2008 Ágúst became Chair of structural geology at Royal Holloway University of London. Throughout his work Ágúst received many grants, for example from the Iceland Science Foundation, the National Research Council of Norway, several oil companies, and the European Union.

## Research

Coming from Iceland, Ágúst's early research focused on volcanotectonics, seismotectonics and geophysical studies on earthquakes and surface deformation. He widened his interests later and for many years his research has been on understanding fractures and fluid transport in the crust in general. He has been using approaches from solid mechanics, fracture mechanics, materials science, fluid dynamics, general continuum mechanics and, most recently, thermodynamics and information theory. The work on fluid transport in fractures has been partly applied (water, oil, and geothermal reservoirs) and partly theoretical (magma transport, earthquake mechanics). Ágúst is also a field geologist and gets many examples from his surveys. Thereby he is one of very few geoscientists both strong in field studies and theory.

Ágúst's work in volcanotectonics and seismotectonics has contributed to the understanding of various physical processes in active volcanoes and seismogenic fault zones. Topics include dyke propagation, caldera formation, active and extinct fault zones. In addition, Ágúst has studied the formation and development of extension fractures, strike-slip faults, normal faults, grabens, and other rift-zone structures and volcanoes. His research also advanced our understanding of geological reservoirs of various types and with various fluids, including magma chambers (active and fossil - such plutons and sills), groundwater reservoirs (aquifers), geothermal reservoirs, oil reservoirs, and gas reservoirs. In this way Ágúst is an eclectic researcher, able to use his knowledge also on apparently very different and distant fields. This is also reflected in that he has recently started to transfer knowledge and methods from structural geology and rock physics to urban studies in geography.

Ágúst's work on rock fractures has included field, analytical and numerical studies. Field areas have been Iceland, Tenerife (Canary Islands), Norway, Wales, England, Scotland, Italy, Hawaii, Israel, and Germany. Part of Ágúst's research has

focused on joints, faults, and mineral veins, and associated permeability development, in layered successions of limestone and shale on the coasts of the Bristol Channel in the UK, where I had the pleasure to work with him for my PhD thesis.

Among Ágúst's main scientific contributions is to stress the importance of mechanical layering on local stresses, fracture propagation, and associated permeability in the crust in general and in geological reservoirs, seismic zones, and volcanoes in particular. He has emphasised the similarities between layered rocks and various industrial composite materials and used many results from the latter field, particularly as regards crack propagation in composite materials, to explain field observations and processes in volcanology, seismic zones, and fractured reservoirs.



**Ágúst Guðmundsson studying calcite veins in the limestone-marl-alternation of the Blue Lias (Jurassic) at the Somerset Coast, England, UK**

## **Publications and Editorship**

Ágúst is the main author of more than 150 scientific papers, mostly in peer-reviewed international journals and books. Most of these are well-cited, total numbers are currently up to several hundreds per year. In addition he published several hundreds of abstracts, reports, and popular articles. He has also been chairman/convenor at many international meetings, in particular of the EGU. Ágúst has also given many popular talks and has been interviewed by radio and television stations in many countries worldwide. When he was a teacher in Iceland, Ágúst wrote two textbooks on astronomy (in Icelandic) for junior college students. In 2011 he published the comprehensive textbook „Rock Fractures in Geological Processes“ (Cambridge University Press), that gave fracturing the dignity it deserves in structural geology and fills a gap in earth sciences. The book therefore also gave the title to the current symposium. Two other books are in progress, to be published within the next years.



Ágúst is associate editor of *Terra Nova* and of *Bulletin of Volcanology*. He is on the editorial board of *Tectonophysics*, *Journal of Geological Research*, *Journal of Volcanology and Geothermal Research (JVGR)*, and the *Scientific World Journal*. Ágúst is the Senior Editor of three special issues: (1) „The Tectonics and Physics of Volcanoes“ (*JVGR*, 2005), (2) „Understanding Stress and Deformation in Active Volcanoes“ (*Tectonophysics*, 2009), (3) „Crustal Stresses, Fractures, and Fault Zones: the Legacy of Jacques Angelier“ (*Tectonophysics*, 2012). Recently he was appointed as Chief Editor of the Structural Geology and Tectonics section of *Frontiers in Earth Science*.

## **Supervision and Collaboration**

In addition to teaching undergraduate, graduate and postgraduate students in topics ranging from applied geology, geothermics, and hydrogeology to numerical and analytical modelling, Ágúst has been guiding students for many years since the time he started at the Nordic Volcanological Institute. He has involved students in nearly all his research topics mentioned above. Ágúst has always been enthusiastically supporting younger dynamic and active researchers. When I was a PhD student I got to know him as a passionate scientist and a dedicated teacher who was nearly always available for answering all questions I had when going into a new field of research.

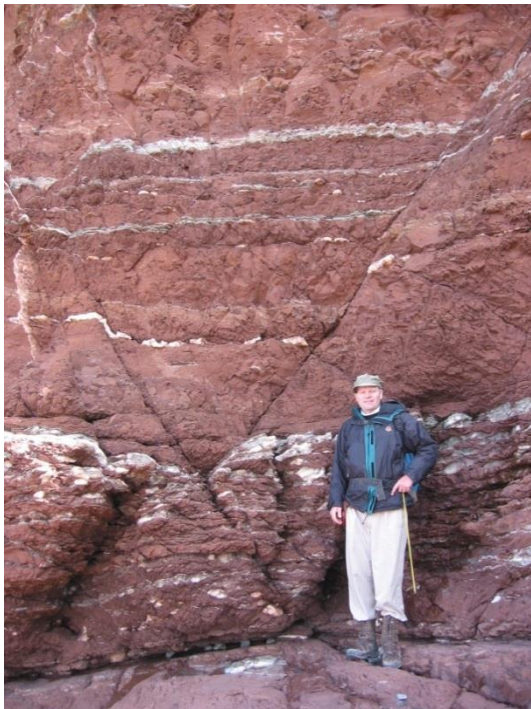
Ágúst has also collaborated with earth scientists throughout Europe and also in Japan and in the USA. Several collaborators are authors of abstracts in this volume.

## **Beyond Science**

Finally a few personal words. When working with Ágúst we have spent many breaks with discussions also about topics outside geology. We share, for example, an interest in classical music – but we have never finally agreed on a shortlist of the three greatest composers ever... However, I learnt a lot about operas and opera singers, in particular he raised my interest for the works of Giacomo Puccini and Richard Wagner. Being in new cities Ágúst always loved spending hours in bookstores, apart from geosciences and music he is also interested in the history of science (particularly of physics and mathematics), astronomy, and biographies. His autobiography, however, he has – to my knowledge – not yet started to write. Convinced to speak for all participants of the symposium I hope he has still many years to do that.



## Fractures, Faults, and Rock Properties



Normal faults forming a graben in Triassic Mercia Mudstone at Watchet, Somerset Coast, UK, with Ágúst Guðmundsson as a scale



# **Models of fracture lineaments – joint swarms, fracture corridors and faults in tight rocks, and their genetic relations**

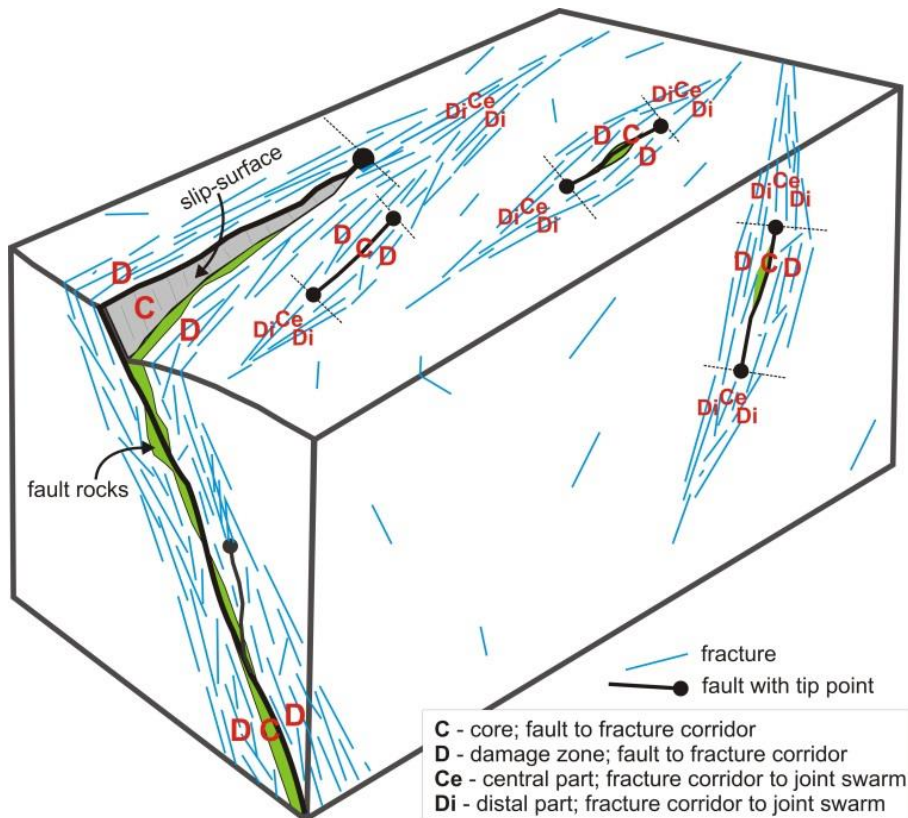
*Roy H. Gabrielsen*<sup>1,3</sup>, *Alvar Braathen*<sup>2,3</sup>

<sup>1</sup> *Department of Geosciences, University of Oslo, Norway*

<sup>2</sup> *University Centre in Svalbard (UNIS), Longyearbyen, Norway*

<sup>3</sup> *UNI Centre of Integrated Petroleum Research (CIPR), Univ. Bergen, Norway*

This study of mappable characteristics of fault and fracture zones addresses fracture lineaments in metamorphic rocks of southern Norway. They can be classified as joint swarms, fracture corridors, or faults, depending on displacement, the fracture mode and patterns, and appearance of fault rocks. Their physical appearance as lineaments seen by remote sensing is not discernible, as they define km-scale tabular zones of high fracture intensity, with an architecture that is delicate in joint swarms and becomes better expressed in fracture corridors and especially faults.

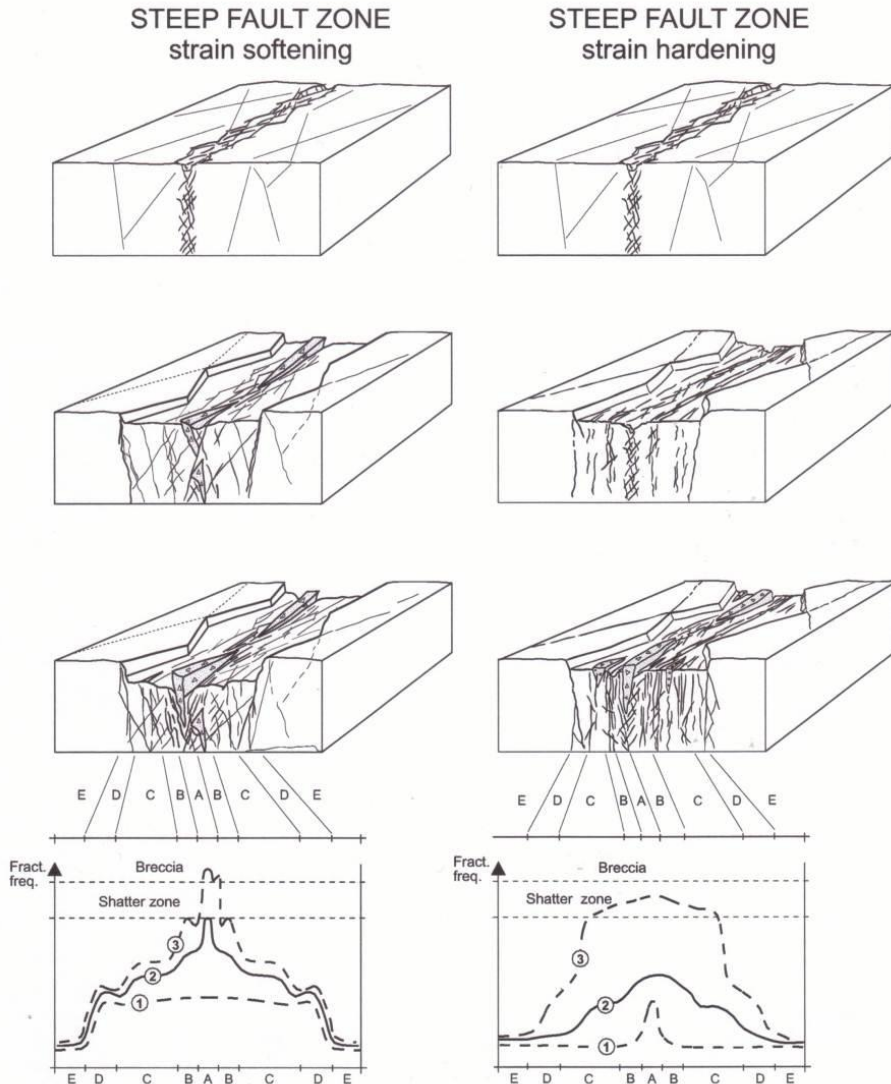


**Figure 1: The architecture of a fracture corridor at the stage of developing into a fault**

Fracture corridors reveal a symmetric fracture zonation on both sides of the fault core, whereas extensional faults tend to have asymmetric patterns with enhanced strain and a wider damage zone in the hanging wall. A fracture lineament can be embraced in subzones A-B (core), which are typically some cm up to some tens of metres wide. Common structural elements are fault rocks/shear zones, lenses, and a network of fractures often with very high fracture frequency. Secondary minerals are common. Outside this, subzones C-D (damage zone) are commonly 20-50-m wide with lower fracture intensity of lineament-parallel fracturing, defining the topographic boundary of the lineament. Mineralisation is rarer. The transitional subzone E of multi-orientation fractures defines the transition to the background fracture system.

We propose a model for the classification and development of fracture lineaments, applying their architecture (intrinsic geometry, spatial fracture pattern and spatial distribution of lithological units) as tools for the systematic description. A development from joint swarm (subzones C-D) to fracture corridor and finally

fault can be envisioned through two end-member scenarios; Progress hardening may cause a widening zone of deformation and even abandonment of the fault core, and a less clearly zoned damage zone, whereas progress softening focuses the strain in to the fault core, favouring a more prominent zonation of the damage zone.



**Figure 2: The development of fault zonation during strain softening and strain hardening**

Several parameters influence the variety in deformational style, fracture frequency and geometry, distribution of fault rocks and mineralized zones of fracture lineaments. In their frequently cited models for crustal-scale fault zones, Sibson (1977) and Scholtz (1988) ascribed the change from cataclastic to crystal-plastic deformation directly to depth and the frictional-viscous transition. Thereby they imply that the evolution of the different types of fault rocks is controlled by temperature, pressure, fluid pressure and strain rate. Detailed field studies suggest that a number of additional parameters contribute to the complexity of fault zones. Examples are grain-size and mineralogy of the deforming rock, other types of pre-existing mechanical anisotropy, and the nature of the fluid phases that invade the fault zone. Considering these processes, it is possible to generate several scenarios, which are characterised by distinct fracture lineament architecture through development from joint swarms to faults.

As joint swarms progress into fracture corridors in early stage(s) of the development of brittle faults, the damage zones are equal until the stage is reached where sufficient strain is accumulated in the central part of the fracture corridor for brecciation and the generation of fault rock to commence as a major through-going structure is developed. As outlined above, the zonation of fracture lineaments is most easily explained in the context of relative age or stage of the fracture systems, distribution of strain intensity within the zone, and the influence of strain localization or dispersion, in ways related to temporal and spatial changes in fault mechanics.

We assign the sum of causes for strain localization or dispersion to the terms *strain hardening* and *strain softening*. The effects of strain softening and strain hardening, based in the aforementioned processes, offer a basic control on the intrinsic fault architecture and fault zone width in both the ductile/plastic and the brittle regimes (Sibson 1977; Chester & Logan 1986). At first glance, the faults, which have reached a mature stage of development, may seem to display great geometrical similarities for those generated during strain-hardening and strain-softening. In both cases, the country rock will be less resistant to erosion after (and during) fracturing. The fracture will therefore define a negative topographic element so that the most intensely strained part of the fault (zones A - B) defines the topographically deepest element, commonly filled by lakes, rivers and creeks. On closer inspection, however, those faults which are developed during dominated strain softening, more commonly reveal a clearer zonation and a well-defined fault core. In cases where the fault core is defined by fault rocks that are resistant to erosion, like mylonites or where mechanically resistant pods of strong country rock are preserved, the fault core may be marked by a zone of topographically positive hills.

Processes behind strain-softening and hardening will in many cases vary through space and time, on a larger scale for instance during fault-driven exhumation of a fault zone with changing rheology from shifting P-T conditions. This will also influence the patch characteristics arresting fault rupture in the breakdown zone model. Accordingly, observable architecture of exhumed major faults zones



attests to a long evolution that is complicated to fully resolve. Despite progress in understanding and new models, as the one presented here advocating systematic characteristics linked to fault growth, more knowledge building in this area is certainly required.

## Conclusions

The outcrop-based study of fracture lineaments in the basement of southern Norway has revealed a systematic architecture, allowing mapping of joint swarms, fracture corridors and faults in a progressive process during fault initiation and growth. All fracture lineaments have a common zonation and, in more complete structures, altogether five zones are distinguished. The two inner zones (zones A and B) are synonymous to the fault core, whereas the three distal zones constitute the damage zones, enveloping the fault core. We link fault growth processes and mechanisms of strain hardening and strain softening to the model of fault architecture.

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# Fluid overpressure of quartz mineral veins in the South Wales coalfield: implication for mechanism of fracture formation in foreland basins

*Tetsuzo Fukunari*<sup>1,2</sup> & *Agust Gudmundsson*<sup>1</sup>

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<sup>2</sup> *Japan Oil, Gas and Metals National Corporation*

In many foreland areas, the orientation of the major fracture set is vertical and parallel to the regional compression direction (Hancock & Bevan 1987). Fracture development in such typical geological settings which can form hydrocarbon accumulations is of great importance to the petroleum industry interested in better understanding of the permeability of oil and gas reservoirs. However, no clear and generally accepted mechanisms for such fracture formation in foreland areas have been established as yet. Here we report the results of a study of bed-scale extension quartz veins formed in sandstone layers in the South Wales coalfield which is one of a series of foreland basins formed in front of northwardly propagating Variscan Orogenic belt.

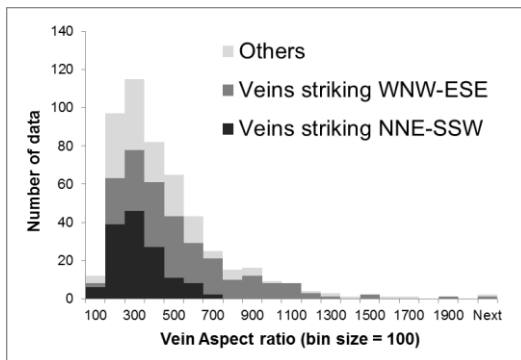
The bed-scale quartz veins can be divided into two relative-age groups based on the field observations: 1) The older group constitutes veins generated during extension perpendicular to the compression of the Variscan Orogeny; 2) The younger group constitutes veins formed during extension sub-parallel to the compression. Those veins are perpendicular to bedding planes in all locations though the beds are strongly folded by the Orogenic movement. This suggests the vein formation somewhat predates or coincides with that of regional folding. That

means both groups formed under the regional north-south compression, even though the formation of younger veins required north-south extension.

Aspect ratios (length of strike dimension divided by thickness) of the veins were measured in the field (Fig. 1), showing that a log-normal size distribution. The geometric mean of the older veins is 246 and that of the younger veins is 436. By using these values with appropriate mechanical properties of the host sandstones which are estimated from laboratory works of Price (1958), fluid overpressure (driving force for fracture propagation) for the quartz vein formation is calculated as around 33 MPa for the older group and 19 MPa for the younger group.

Fluid overpressure is generally considered as the combined effect of initial excess pressure, buoyancy and differential stress. A lack of carbonate minerals inside the quartz veins denies the possibility that the geological fluid having formed the quartz veins was supplied from the Dinantian Carbonates underlying the South Wales coalfield. This suggests the effect of buoyancy was less than 10 MPa. By assuming that the initial excess pressure was the same as the tensile strength of the host sandstones, 5 MPa, differential stresses for the older and younger vein formations are calculated to be at least 18 MPa and 4 MPa, respectively.

These results suggest a local stress field within the sandstone layers initially induced east-west extension with maximum principal stress of about 13 MPa, which changed to north-south extension with nearly zero maximum principal stress under the regional north-south compression of Orogenic movement.



**Figure 1: Size distribution of vein aspect ratios.**

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# Effects of facies and diagenesis on fracture propagation and reservoir permeability in limestone-marl alternations

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## Introduction

Mechanical layering can act as barrier to fracture propagation, reducing the potential for interconnected fracture networks (cf. Brenner & Gudmundsson, 2004) and, consequently, reservoir permeability. The majority of studies on fracture propagation in multiple strata focus on mechanical contrasts at interfaces, neglecting the effects of lithology, facies and diagenesis. Aims of this study, however, are to determine (i) the effects of sedimentological processes on fracture propagation, and (ii) a maximum marl thickness for the definition of a “mechanical section” in which most fractures propagate through multiple strata despite of mechanical layering.

We examined the distribution of 6078 fractures using a modified scan-line method in six different sections of limestone-marl alternations (Fig. 1) in the Blue Lias of the Bristol Channel. To describe vertical fracture propagation through multiple layers, we distinguish stratabound and non-stratabound fractures (Odling et al., 1999).

## Effects of sedimentological processes

The data reveal that fracture densities vary significantly despite of similar bed thicknesses. In particular, densities differ between laterally continuous beds (i.e., well-bedded limestones, LS) and beds with bedding plane irregularities (i.e. semi-nodular limestones, SNL). In addition SNLs reveal a wide range of fracture spacing, fractures in LS are more regularly spaced. Furthermore SNL show higher percentages of non-stratabound fractures than LS. Therefore, contrary to the com-



**Figure 1: Different sections from well-bedded limestones to semi-nodular limestones and from limestone-dominated to marl-dominated alternations.**

mon approach in studies on fracture propagation in multiple strata, SNLs and LS must be distinguished.

To test the effects of sedimentary facies and diagenesis we compared the Blue Lias Fm in three closely located sections in Wales (distances < ca. 500 m). Each selected succession comprises three stiff limestone beds and two soft marl layers

(with almost the same thickness) interbedded in thicker marl layers. Despite of the close proximity, however, all these successions reveal different sedimentological and diagenetic features and are characterized by dissimilar percentages of stratabound and non-stratabound fractures.

The first succession comprises well-bedded LS beds due to complete lithification during earliest diagenesis (Fig. 2A). This succession is characterized by low percentages of non-stratabound fractures in LSs and marls.

The second succession reveals evidence for differential compaction (Fig. 2B; i.e. early diagenesis due to dissolution and cementation of carbonate; cf. Westphal et al. 2000). This succession reveals notably high percentages of non-stratabound fractures in LS and SNL beds as well as in marl layers.

The third succession is predominantly characterized by SNL beds (Fig. 2C). The irregular character is primarily due to bioturbation but was secondarily enhanced by significant physical compaction (i.e. during late diagenesis due to overburden pressure during burial). This succession also reveals high percentages of non-stratabound fractures in LS and SNL beds, but only low percentages in the marl layers.

## **Maximum marl thickness**

Most fractures propagate into, but do not completely penetrate, marl layers. Since the thickness of a marl layer is particularly crucial for the formation of a “mechanical section”, the required maximum marl thickness is of special interest. For this reason we distinguished different types of marls based on lithology and quantified the maximum layer thicknesses through which fractures propagate. Respective findings will then be discussed in the presentation.

## **Implication on reservoir permeability and exploration**

The overall characteristics of beds within a succession are the product of sedimentary and diagenetic processes. This has implications concerning the prediction of permeability in fluid reservoirs (e.g. geothermal-, hydrocarbon- and groundwater-exploration). For successful exploration the effects of all these processes on fracture propagation in layered reservoirs need to be understood. The results also demonstrate the general difficulty to extrapolate outcrop data to the subsurface. Limestone-marl alternations that are strongly affected by diagenetic processes, however, are particularly problematic since it is more difficult to find a representative elementary volume (REV) for this kind of rocks.

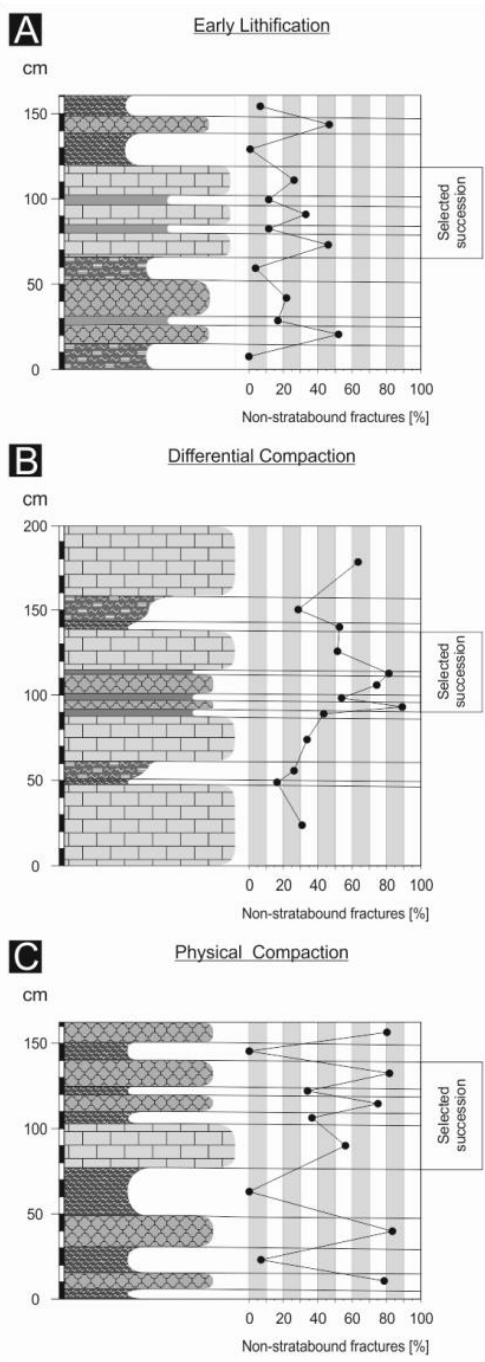


Figure 2: Sedimentological Section and percentage of non-stratabound fractures.



## Acknowledgements

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# Sub-horizontal faults in clayey layers: macro- and microstructures

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## Faults in layered rocks

Faults crosscutting multilayer systems show structural complexities induced by the mechanical layering. Fault refraction (dip changes), preferential linkages within a layer or at layer interfaces, variations in the displacement gradient and displacement anomalies in relation with the lithology (e. g., Peacock and Zhang, 1993; Childs et al., 1996; Roche et al., 2012a) are commonly observed. Several processes control the development of these faults, like preferential nucleation, fault linkage, fault arrest and restriction, under a variable stress profile throughout the layering (e. g., Schöpfer et al., 2006; Larsen and Gudmundsson, 2010; Roche et al., 2013). Bedding-parallel faults in the compliant units of multilayer systems such as clay, chalk and salt units are very common and strongly interact with and control many aspects of the faults forming obliquely to the bedding (Gross et al., 1997; Roche et al., 2012a and b).

## Sub-horizontal faults and normal faults

We consider several examples of sub-horizontal faults in multi-layered clay/limestone systems in the Southeastern French basin and its western margin in Ardèche. These faults below are referred to as Clay Horizontal Faults (CHF) following the description of Roche et al. (2012a). They are localized within 30 cm to 2m thick clayey layers and interacted with meso-scale normal faults. All the CHF dip generally lower than  $10^\circ$  and are highlighted by a thin, a few millimeter thick, band of calcite which carries a striation with polarity.

Field data, including detailed mapping of the fault segments, direction and displacement data, and measures characterizing the spatial arrangement of the fractures highlight several aspects. First, the CHF and the normal faults developed during the same extensional phase. Notably CHF also exist far from the normal faults, cutting otherwise intact clay units. Second, CHF controlled the growth of the normal faults. Some CHF acted as restrictors, i. e. the normal faults abutted against them and accumulated vertical displacement without vertical propagation. Others link high dipping normal fault segments and thus allowed the transfer of the displacement from one fault segment to another.

## Microstructures in sub-horizontal faults

Microstructural analysis provided a detailed identification of the internal structure of the CHF. We examined thin sections cutting the CHF, the normal fault segments, and the clay units far from fractures. The CHF are composed of sub-parallel bands of calcite. The various internal structures are related to different syn-crystallization kinematics. Pluri-micrometric to millimetric elongated crystals indicate an opening in a direction orthogonal to the fracture edges. En echelon crack-seals at high angle to CHF plane and dominos of calcite are also observed and formed as a result of shear movements. The CHF may locally show a brecciated aspect, being there composed of angular clasts of calcite and clays. Overgrowth figures, eroded crystals, and color contrasts observed in cathodoluminescence show a more or less pluriphasic fluid circulation depending of the studied sites.

Scenarii of the deformation mechanisms which occurred along the CHF are built using these microstructural observations. In all cases, the activity of the CHF during their development and interaction with the normal faults include several kinematics. The latter correspond to a mode I opening, the formation of Riedel fractures in a distributed shear zone, and slips on discrete fractures. Later movements, including closing and stylolitisation of the CHF overprint this early history.

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# Characterization of fault zones in Triassic Muschelkalk limestones of the Upper Rhine Graben with regard to geothermal exploration

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The characterization of fault zones is of particular importance in geothermal reservoirs since there may be great effects on fluid flow (Philipp, 2007). Fault zones generally consist of two major hydromechanical units: the fault core and the damage zone, surrounded by the host rock (Caine et al., 1996). To improve predictions of fracture system parameters for each unit and resulting estimations of reservoir permeabilities at depths we perform outcrop analogue studies. We analyze Middle Triassic Muschelkalk limestones that form one geothermal reservoir formation in the Upper Rhine Graben (southwest Germany) in quarries on its eastern graben shoulder (Fig. 1).

We measure the orientations and displacements of various fault zones and characterize the fracture systems within the fault zone units and in the host rocks. Our studies show that damage zones are well developed even in smaller fault zones. Their fault cores, however, are narrow compared with that of fault zones with large displacements and comprise brecciated material, clay smear, host rock lenses or zones of mineralization.

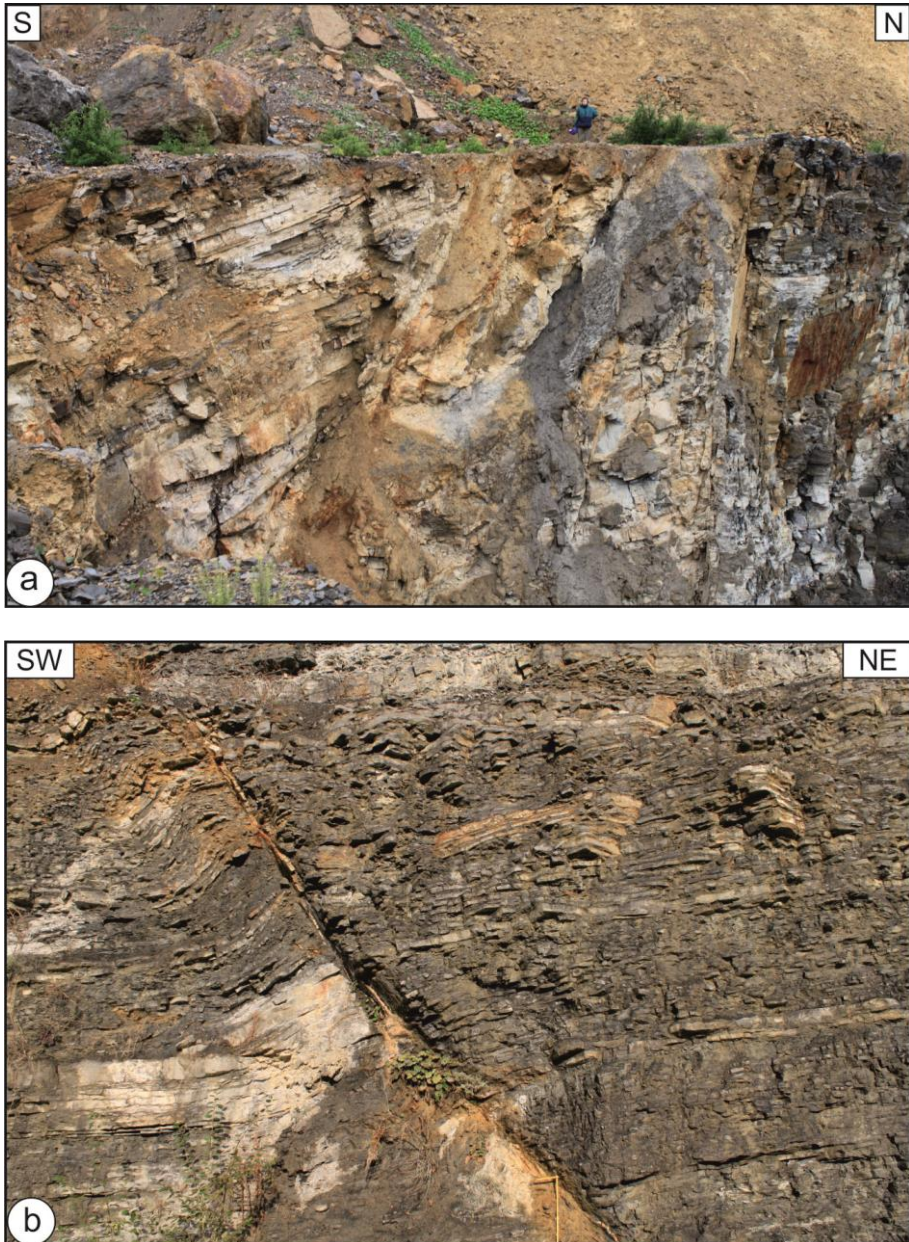


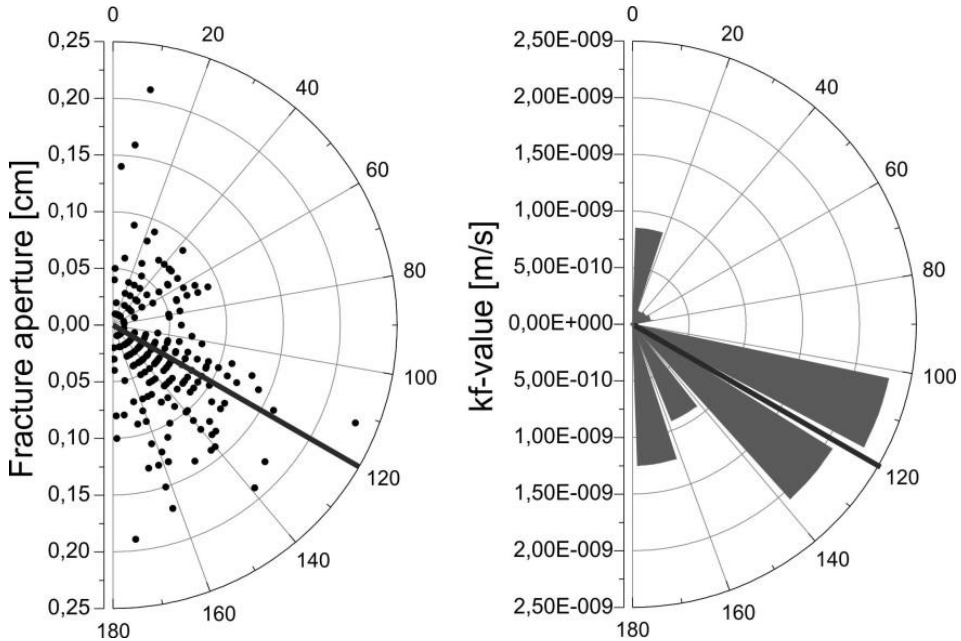
Figure 1: Field examples of fault zones in Muschelkalk from the quarries a) Nußloch, b) Knittlingen



Based on the field data we use analytical models to estimate the permeabilities of the analyzed fracture systems. Results show increased fracture frequencies in the fault zone damage zones and larger fracture apertures parallel or subparallel to fault zone strike that lead to enhanced permeability compared with other orientations. Mineralized fractures accumulated in this direction in the “Nussloch”-quarry indicate that these fractures were pathways for fault zone parallel fluid flow in the past. This shows that open fractures with orientations parallel to fault zones may be pathways for fault zone parallel fluid flow in geothermal reservoirs. By contrast, well-developed fault cores may be potential barriers for fluid flow in inactive fault zones (e.g. Agosta, 2007; Caine et al., 1996; Gudmundsson, 2011). Figure 2 shows the fracture aperture and the calculated permeability (after Bear, 1993) in each case versus strike direction of the fractures exemplified for the “Nussloch”-quarry.

To build numerical models to analyze local stress fields and effects on fracture propagation for different fault zone types and geometries information on rock mechanical properties is necessary. Therefore we take representative rock samples in the quarries to determine uniaxial compressive and tensile strengths as well as Young’s Moduli in the laboratory. Additionally we measure the rebound hardness distribution across fault zones with a “Schmidt-Hammer” to analyze mechanical property variations. First results show that the rebound hardness increases with increasing distance from the fault core.

The presented studies help to predict the permeability of fault-related geothermal reservoir rocks and minimize the exploration risk of geothermal projects. This project is part of the Research and Development Project AuGE (Outcrop Analogue Studies in Geothermal Exploration). Project partners are the companies Geothermal Engineering GmbH and GeoEnergy GmbH as well as the Universities of Heidelberg and Erlangen. The project is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) within the framework of the 5th Energy Research Program (FKZ 0325302).



**Figure 2: “Nussloch”-quarry: Fracture aperture versus strike (left) and kf-value versus strike (right) in the “Nussloch”-quarry. The strike direction of the main fault zone (120°) is marked by the thick black line in each diagram.**

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# **Infrastructure and mechanical properties of a normal fault zone in Bunter sandstone (Lower Triassic) in the Upper Rhine Graben**

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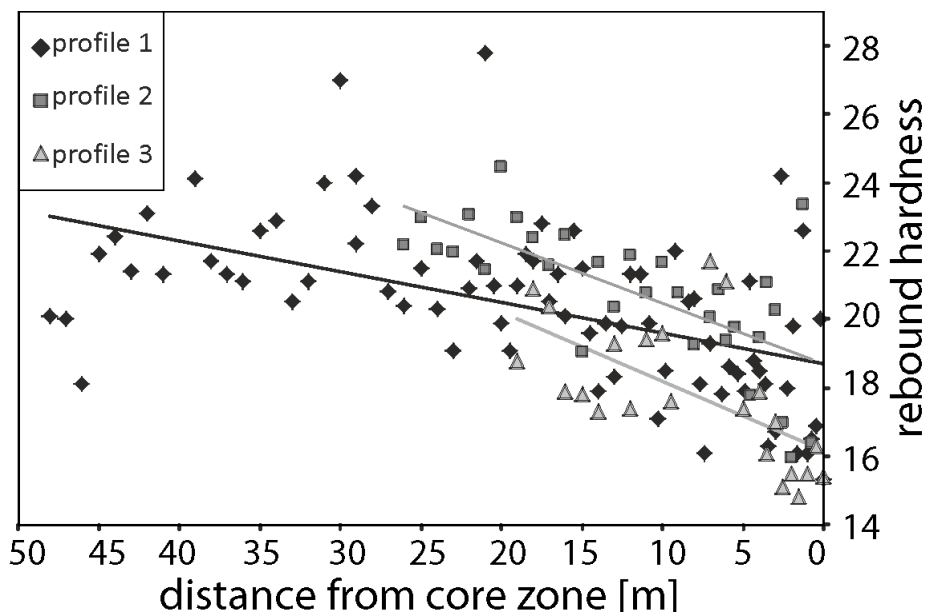
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Due to high drilling costs of geothermal projects, it is economically sensible to assess the potential suitability of a reservoir prior to drilling. Fault zones are of particular importance, because they may enhance fluid flow, or be flow barriers, respectively, depending on their individual infrastructure (Caine et al., 1996; Sibson, 2000; Agosta et al. 2007; Faulkner et al., 2010).

Outcrop analogue studies are useful to analyze the fault zone infrastructure and thereby increase the predictability of fluid flow behaviour across fault zones in the corresponding deep reservoir (Reyer et al., 2012). The main aims of the present study are to 1) analyze the infrastructure and the differences of fracture system parameters in fault zones and 2) determine the mechanical properties of the faulted rocks. Therefore we measured the differences of structural elements within fault zones by using a modified scan line method. For each fracture we noted its position, type, orientation (strike direction and dip angle), mineralization and its termination (e.g. free tip, truncated by another fracture, or covered). Furthermore we took representative rock samples to obtain Young's moduli, compressive and tensile strengths in the laboratory. Since fractures reduce the stiffnesses of in situ rock masses (Walsh, 1965; Priest, 1993) we use an inverse correlation of the number of



Figure 1: Fault zone in Bunter sandstone (Lower Triassic) in the quarry Cleebourg, Alsace, France and enlarged details.



**Figure 2: Rebound hardness of the rock mass determined from three different profiles in the footwall started at the fault core margin.**

discontinuities to calculate effective (in situ) Young's moduli to investigate the variation of mechanical properties in fault zones (cf., Priest, 1993). In addition we determine the rebound hardness, which correlates with the compressive strength measured in the laboratory, with a "Schmidt-Hammer" in the field (Barton and Choubey; 1977). This allows detailed maps of mechanical property variations within fault zones.

The field measurements were performed at one outcrop located in the Upper Rhine Graben at the western Graben Shoulder in Alsace, north France, that exposes Trifels-Sandstone belonging to the Triassic Lower Bunter. The outcrop at Cleebourg exposes the damage zone of the footwall and a clearly developed fault core of a NNW-SSE-striking normal fault (Fig. 1). The approximately 15 m wide fault core consists of fault gouge, slip zones, deformation bands and host rock lenses. Intensive deformation close to the core led to the formation of a distal fault core, a 5 m wide zone with disturbed layering and high fracture frequency. The damage zone also contains more fractures than the host rock. Fracture frequency and connectivity clearly increase near the fault core where the reservoir permeability may thus be higher, the effective Young's modulus lower.

Similarly the Schmidt-Hammer measurements show that the rebound hardness, or the compressive strength, respectively, decreases near the fault core (Fig. 2).

This Project is part of the Research- and Development Project “AuGE” (Outcrop Analogue Studies in Geothermal Exploration). Project partners are the companies Geothermal Engineering GmbH as well as the Universities of Heidelberg and Erlangen. We thank the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) for funding the project in the framework of the 5th Energy Research Program (FKZ: 0325302). Also thanks to the owner of the quarry for the permission to perform our field studies.

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# **Applicability of failure criteria and empirical relations of mechanical rock properties from outcrop analogue samples for wellbore stability analyses**

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## **Introduction**

Knowledge of failure criteria, Young's modulus and uniaxial and tensile strengths, are important to avoid borehole instabilities and adapt the drilling plan on rock mechanical conditions (McLean and Addis, 1990; Moos et al., 2003). A considerable reduction of the total drilling costs can be achieved in this way. This is desirable to enlarge the profit margin of geothermal projects which is rather small compared with hydrocarbon projects.

## **Approach**

Because core material is rare we aim at predicting in situ rock properties from outcrop analogue samples which are easy and cheap to provide. The comparability of properties determined from analogue samples with samples from depths is ana-

lysed by performing conventional triaxial tests, uniaxial compressive strength tests and Brazilian tests of both outcrop and equivalent core samples. Equivalent means that the outcrop sample is of the same stratigraphic age and of comparable sedimentary facies and composition as the associated core sample. We determined the parameters uniaxial compressive strength (UCS), Young's modulus, and tensile strength for 35 rock samples from quarries and 14 equivalent core samples from the North German Basin. A subgroup of these samples, consisting of one volcanic rock sample, three sandstone and three carbonate samples, was used for triaxial tests. In all cases, comparability of core samples with outcrop samples is evaluated using thin section analyses.

## Results

For UCS versus Young's modulus and tensile strengths, linear- and non-linear regression analyses were performed. We repeat regression separately for clastic rock samples or carbonate rock samples only as well as for outcrop samples or core samples only. Empirical relations have high statistical significance and properties of core samples lie within 90% prediction bands of developed regression functions of outcrop samples (Figure 1).

With triaxial tests we determined linearized Mohr-Coulomb failure criteria, expressed in both principal stresses and shear and normal stresses, for outcrop samples. Comparison with samples from larger depths shows that it is possible to apply the obtained principal stress failure criteria on clastic and volcanic rocks, but less so for carbonates. Carbonate core samples have higher strengths and develop larger angles between fault normal and main principal stress than outcrop samples. This considerably reduces the residuals between outcrop failure criteria and core test results (Figure 2). Therefore, it is advised to use failure criteria, expressed in shear and normal stresses, for prediction of core sample failure conditions.

**Figure 1 (next page, above):** Lithologically separated regression analyses for  $E_s$  vs. UCS (a, b) and UCS vs.  $T_0$  (c, d) calculated for outcrop (black points) and core samples (red points), including 90% prediction and confidence bands, as well as outcrop samples only (see key). Error bars represent standard deviations of all measurements of one sample.

**Figure 2 (next page, below):** Linearised Mohr-Coulomb failure criteria, calculated for triaxial test sequences of outcrop samples (blue diamonds), expressed in both principal stresses and shear/normal stresses with results of equivalent core samples (red squares) for exemplified sandstone and carbonate samples (cf. Reyer and Philipp, submitted).



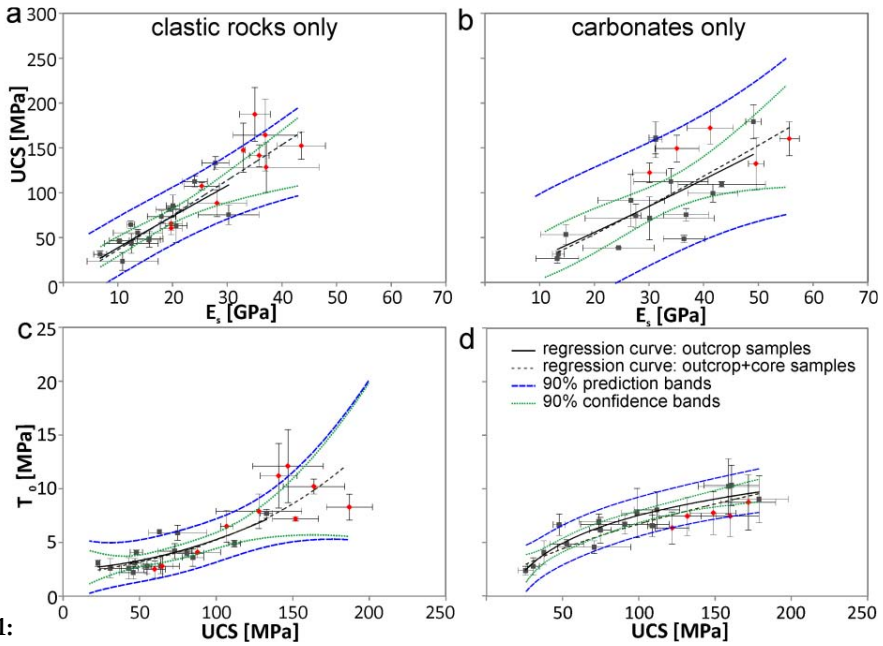


Fig.1:

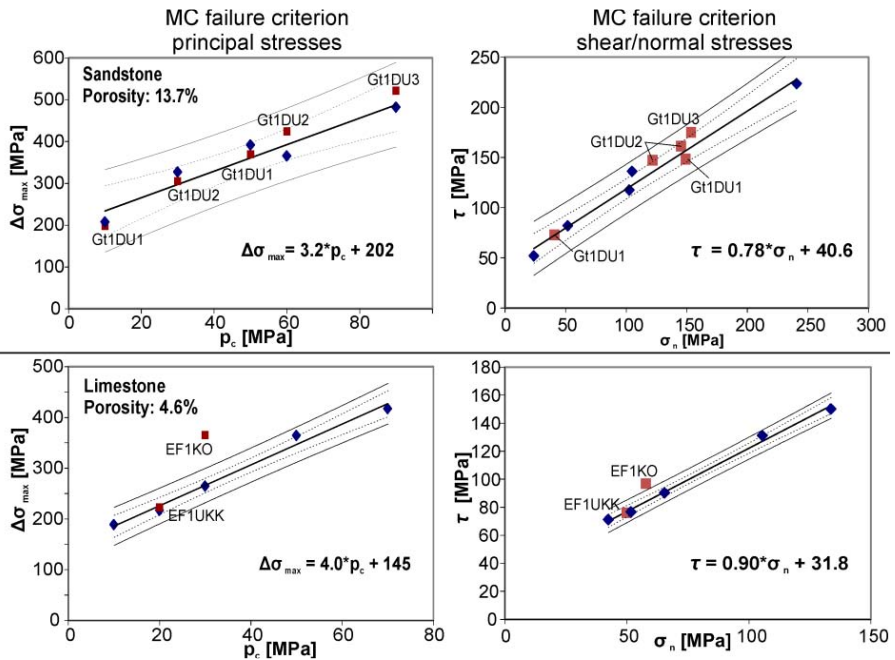


Fig.2:

## Conclusions

We conclude that it is possible to apply failure criteria on samples from depth if the comparability, especially textural comparability and similar porosities, of chosen outcrop analogues samples is ensured. Applicability of empirical relations of UCS with Young's modulus and tensile strength to rocks at depths is expected. Presented results may help predict mechanical properties for in situ rocks, and thus develop suitable geomechanical models for the adaptation of the drilling strategy on rock mechanical conditions.

## Acknowledgements

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## Volcanotectonics



Ágúst Guðmundsson with students studying dykes in a road cut in Tenerife



# Shallow magma chamber formation and evolution

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Shallow magma chambers act as both sources and sinks to magma and are defined to be magmatic bodies that are partially or totally molten replenished with magma from a deep seated reservoir. Recent studies suggest that shallow magma chambers may have evolved from sills. However, for this to occur certain conditions must be satisfied: (1) the sill must be thick, in the order of 10s of metres due to either magma accumulation or sill complex amalgamation, (2) relatively constant magma is injected in order for the magma chamber to remain at least partially molten.

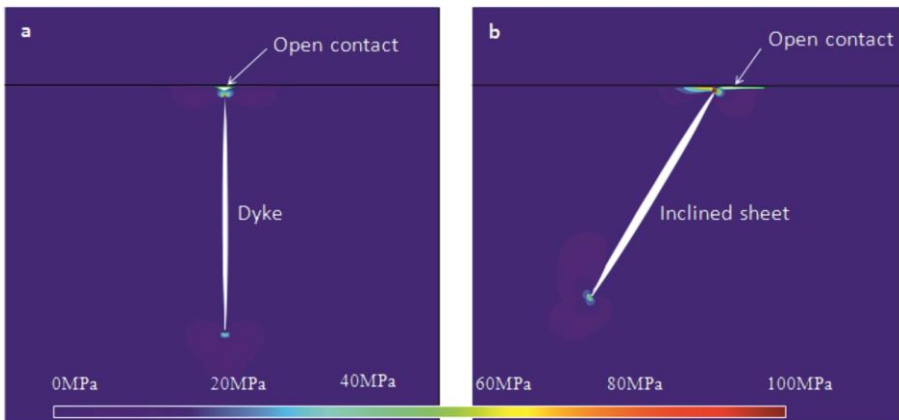
Here I will present numerical models (finite element) based on geophysical and field studies on how individual sills have the ability to evolve into shallow magma chambers. Sills take a variety of forms: straight, concave or stepped, but seismic studies show that magma chambers at mid-ocean ridges illustrate a reasonably straight, smooth, ellipsoidal geometry rather than a network of sills and dykes.

First, the emplacement of sills must be considered. Numerical models indicate that sills are often emplaced at an interface, dominantly weak contacts between layers of contrasting stiffnesses, e.g. pyroclastics and lavas. When a dyke propagating from a deeper seated reservoir meets a weak contact there are three scenarios in which the dyke may respond: (1) cessation of the dyke at the contact, (2) propagation of the dyke through the contact or (3) deflection of the dyke at the contact. It is scenario three that determines the emplacement of sills.

Sill emplacement is favourable at interfaces between soft rocks (e.g. pyroclastic rocks) and stiff rocks (e.g. basaltic lava flows); these conditions are common in the

upper crust. There are three mechanisms which may act simultaneously although one mechanism may dominate for a dyke to be deflected at a contact. The first mechanism is Cook-Gordon debonding where the contact has the ability to open up ahead of the propagating dyke due to the high tensile stresses generated by the dyke tip. The second mechanism is a stress barrier; this is where there is an unfavourable stress field for vertical propagation and encourages sill emplacement i.e. the maximum principal compressive stress has been rotated ninety degrees from being vertical (favourable for dyke propagation) to being horizontal (favourable for sill emplacement) in the upper layer. The third mechanism is elastic mismatch, where there is a difference in mechanical properties (Young's modulus and material toughness) between the layers above and below the contact.

Numerous numerical models were run and analysed with respect to shallow magma chamber evolution with the results as follows: (1) Sills grow by elastic-plastic deformation and partial melting of the host rock in which it is emplaced. (2) Subsequent dyke injections are arrested at the initial sill, as the stress field has been rotated at this point and new sills form around the initial sill, generating a sill complex. The dyke injection rate must be high in order for the sill complex to remain, at a minimum, partially molten to allow for the formation of a potential shallow magma chamber. (3) For the sill to grow and evolve into a shallow magma chamber there is deflection of the overburden (and to some extent the underburden) at the centre of the inflating sill.



**Figure 1:** Finite element model illustrating how a dyke propagates towards a weak contact and either may be (a) singly deflected or (b) doubly deflected to form a sill. Colour contours represent minimum compressive principal stress which is greatest at the dyke dip allowing the weak contact to open up ahead of the dyke.

# Rock fracture as a precursor to volcanic eruptions

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About 50 volcanoes are in eruption each year. Although magma occasionally escapes through open conduits, it more commonly breaks open a new pathway through the crust. As a result, eruptions are frequently preceded by surface deformation and seismicity.

The precursory signals show remarkably constrained patterns of behaviour, encouraging the view that deterministic, short-term forecasts of eruptions are feasible. Particularly robust are accelerating rates of occurrence of volcano-tectonic (VT) events, independent of magma composition and tectonic setting (Voight, 1988; Bell and Kilburn, 2010). The range of precursory VT behaviour has been encapsulated by the empirical Voight criterion for self-accelerating processes (Voight, 1988), which yields trends between the limiting cases when the rate of VT seismicity increases (1) exponentially with time and (2) exponentially with the number of events. Comparable behaviour has been observed in the laboratory among increasing rates of acoustic emissions (AE) before the bulk failure of rock samples. The apparent universality of fracturing trends is consistent with precursors being controlled by structural conditions that can develop at length scales from laboratory samples to the crust.

At the field scale, VT events typically occur within a crustal volume  $\sim$ km across between a magma body and the surface (Kilburn, 2003). Individual se-

quences involve  $\sim 10^3$ - $10^5$  VT events, maximum strains of  $\sim 10^{-3}$ - $10^{-2}$  and VT-event magnitudes of 0-2, which indicate slips along faults  $\sim 0.01$ - $0.1$  km across and less than 10% of the dimensions of the deforming crust. Detected events occur throughout the deforming crust during the entire precursory sequence, without evident changes in their magnitude-frequency distribution or a strongly-preferred upward migration with time.

The VT characteristics are consistent with slow macroscopic fracturing around a distributed population of weakly-interacting faults, much smaller than the volume being deformed (or, for AE in the laboratory, by the movement of small cracks that are distributed throughout a sample). Approximating the crust to an elastic-brittle material, the external energy supplied from, for example, a pressurized magma body can be accommodated by increasing the deformation between atomic bonds within intact rock, and by driving fault movement. Although they commonly operate together, the processes yield two limiting regimes, corresponding to when most of the energy is either stored by deforming intact rock, or is consumed by faulting.

The physical limits correspond to the empirical limits of the Voight relation. Applying conservation requirements at the macroscopic and microscopic scales, the limiting accelerations in VT event rate are found to depend exponentially on the ratio ( $S_{\beta}/S^*$ ), where  $S_{\beta}$  is the mean stress around fault margins and  $S^*$  is the thermodynamic energy per unit volume stored in rock due to its temperature and effective confining pressure (confining pressure - pore-fluid pressure) before deformation begins (Kilburn, 2003, 2012). The new model shows that, for the rates of pressure increase common during volcanic crises, deterministic forecasts are in practice likely to be reliable only days before eruption. Should longer times be required to implement emergency procedures, then decisions may need to depend on statistical evaluations alone.

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# **Influence of previous structures in shallow feeder dyke-eruptive fissures propagation**

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## **Introduction**

Volcanic unrest periods are usually characterized by the uncertainty of how an eruption occurs and evolves. The development of possible scenarios of volcanic eruptions is usually focused on the study of previous eruptive styles. However, local stress associated to previous structures may also be studied in order to forecast fissure eruptions, since feeder dykes can propagate easily through them (Gudmundsson, 1992; Galindo and Gudmundsson, 2012).

Here we present the results of the study on the effects of previous faults in feeder dykes and their related eruptive fissures propagation based on numerical models and field observations in Tenerife and Lanzarote (Canary Islands).

## **Volcano-tectonic setting**

Tenerife and Lanzarote are volcanic islands that belong to the Canary archipelago. Their formation is related to a mantle plume in the quasi-stationary African plate. Common features on these islands are active rift zones, where eruptive fissures, dykes and scarce normal faults are the main volcano-tectonic structures.

## Field observations

Volcanic fissures, feeder dykes, and faults have been recognized and studied in the two islands, with special emphasis placed on the influence of faults in feeder dyke-eruptive fissure propagation. Three examples have been selected. In all of them fissure orientation is parallel to the rift trend where they are located.

The eruptive fissure of Montaña Colmenas in Tenerife trends perpendicularly to a listric fault. The main and more active vent along this fissure is located in the central part of the fissure, just at the intersection between the fissure and the fault. From this vent (a cinder cone) most lava flows were issued. The rest of the fissure is composed of small spatter cones.

The Arafo fissure is part of a triple historic eruption in Tenerife. This eruption started close to the central part of the island and later migrated towards the NE. Three eruptive fissures were formed: two of them very close and a third one several kilometers far away from the others. This third fissure was formed at the Pedro Gil caldera fault, suggesting that the magma propagated laterally till it found the fault.

Montaña Tinastoria is a fissure eruption in Lanzarote that shows two main underlapped segments. One of them is oriented roughly parallel to the rift zone. The other, change in direction around 20°, when it propagates along a lateral normal fault of a graven valley.

## Numerical models

Based on field observations, three possible scenarios were run with the finite element program ANSYS ([www.ansys.com](http://www.ansys.com)). We considered a homogeneous and isotropic crust. The eruptive fissure and the discontinuities were modeled as holes. In the case of the eruptive fissures, an overpressure of 10 MPa was applied. The host rock was modeled with a Poisson's ratio and a Young's modulus of 0.25 and 20 GPa, respectively.

In the first model, the eruptive fissure is perpendicular to a discontinuity. This discontinuity causes a disturbance in the maximum principal tensile stress field, and two branches are formed at the side of the eruptive fissure close to the discontinuity, giving two symmetric concentration stress areas at the discontinuity. The coincidence of the maximum principal tensile stress concentration and the tensile stresses (Von Misses) at these two points suggest that the eruptive fissure will change its trajectory as it approaches the discontinuity. This is emphasized by the  $\sigma_1$  trajectories that suggest a lateral propagation of the eruptive fissure and a perpendicular propagation through the discontinuity.

The second model is similar to the first, but in this case the discontinuity is oblique to the eruptive fissure trend. The stress and Von Misses concentration at the discontinuity is now located only at the side that is closer to the eruptive fis-

sure. The  $\sigma_1$  trajectories show that the eruptive fissure will propagate first laterally, changing to a perpendicular trend close to the discontinuity.

Finally, if the eruptive fissure trend is parallel to an offset discontinuity, a concentration of tensile and shear stress occurs at the eruptive fissure tips and at the discontinuity. Thus, the eruptive fissure will offset and propagate through the discontinuity.

## Results

The results indicate that in the first scenario, although the eruptive fissure cut the fracture without important changes in orientation, the discontinuity may easily channel the magma through the fault plane towards the surface, since the main and more active eruptive vent in our field example is located just at the intersection between the eruptive fissure and the fault. Probably the eruption started at the intersection of both structures and then propagated laterally towards both sides where only spatter cones were formed.

If the fault is parallel and offset, like in the second scenario, the eruptive fissure is captured by the discontinuity and the magma flows through the fracture.

Finally, when the dyke approaches an oblique fracture, it is segmented and propagates towards the closest part of the fault, later following the fault direction.

## Discussion and conclusions

The intersection of an eruptive fissure and a fault always has effects on the feeder dyke-eruptive fissure propagation, either changing the fissure orientation or expediting the movement of magma towards the surface. For instance, detailed volcano-structural studies may help to understand the relationship between them and to create more reliable eruptive scenarios.

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# Magma and tectonics along divergent plate boundaries: insights from field and modelling data

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Recent data have demonstrated that magma emplacement may play a major role during discrete rifting episodes, also controlling the development of normal faults and the morphology of the rift itself. Here we use field data and analogue modeling to better constrain the role of magma and regional tectonics on the development and morphology of the rift.

In order to understand the mechanism of formation of the faults along rifts, as well as their possible relationship to magmatic activity, we analyzed selected portions of the oceanic ridge of Iceland and the Main Ethiopian Rift (Ethiopia; MER). Systematic measurements of the termination of the faults along the rift axis have been carried out, in order to define their sense of propagation (upward vs. downward) and possible relation to magmatism. The results show that, depending upon the area, there is a clear prevalence of fault propagation folds or extension fractures at the fault tips. While fault propagation folds are more common along the MER and Reykjanes Peninsula, open fractures predominate in the North Volcanic

Zone. In some cases (Reykjanes, southern termination of Krafla magmatic segment), contractional structures have been observed at the base of the tilted hanging wall of faults, suggesting the activity of fault propagation folds. In addition, surveys along the eroded parts of the rift zone in eastern Iceland, at a paleodepth of approximately 1 km, reveal that the predominant mechanism of extension of the crust is diking, with very limited faulting.

To better understand any role of magma on the evolution of the geometry and kinematics of rift, we also use analogue models of dike intrusion. Laser-scanner and Particle Image Velocimetry (PIV) techniques have been used allowing us to quantify and reconstruct the time evolution of the rift development. In particular, we study the deformation of the host rock resulting from the emplacement of multiple dikes. The results show two different patterns depending upon the depth to the top of the dike zone. For shallower intrusion zones, a set of conjugate normal faults propagates downward, forming a graben above the dikes. For deeper intrusion zones, the normal faults form after the development of a pair of high angle reverse faults propagating both downward and upward.

We propose a preliminary working hypothesis, where: 1) the surface deformation along rift zones, as well as their morphology, appears largely controlled by the emplacement of dikes at depth; the normal faults observed at the surface are mostly dike induced, as their frequency decreases sharply below the injection depth; 2) the deformation pattern and the sense of propagation of the faults seems related to the depth (or immaturity) of the intrusive zone: deeper intrusive stocks, related to less mature magmatic systems (MER; Reykjanes, periphery of Krafla) induce grabens with upward propagating reverse faults, fault propagation folds and compression at the surface; shallower stocks, related to more mature magmatic systems (central Krafla) induce grabens with downward propagating normal faults.

# The formation and role of caldera ring faults

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There is still much to understand about the physical processes connected with the formation and development of caldera bounding ring faults. This topic is especially important as the location and dynamics of a ring fault may control the evolution of future volcanism in a caldera. Furthermore, caldera forming eruptions constitute some of the most devastating natural events in Earth's history and as such need to be better understood.

Here we present field observations of a well exposed section of a ring fault in a Tertiary volcano in Western Iceland. The ring fault in the Hafnarfjall central volcano is believed to have accommodated up to 200 m of vertical displacement (Franzson, 1978). Due to subsequent erosion to a depth of >1 km, this unique setting allows the observation and interpretation of processes which occur along the fault at great depth.

We create a model of fault development based on field observations, analytical and numerical modelling techniques whereby a ~ 5 m section of the ring fault acts as a fault core with a low strength. This core is surrounded by a 30 m damage zone of brecciated and highly porous lavas. The implications of this fault zone are that younger inclined sheets propagating from a central shallow magma chamber (Gautneb, 1988) become deflected on contact with the fault and change their attitude to coincide with the fault direction. The model aids the explanation of the

prevalence of type-M and Ms (Geyer and Marti, 2008; Walker, 1988) volcanism within calderas.



**Figure 1:** View East of an exposed section of caldera ring fault at the Hafnarfjall central volcano in W. Iceland. The dip of lavas increases from 10° S, North of the fault (outer caldera) to over 20° S to the South of the fault (inner caldera). Vertical displacement along the fault is estimated in the region of 200 metres.

In future models we hope to investigate the importance of anisotropy in controlling the development of caldera ring faults to understand if certain volcanic structures are more prone to vertical or lateral collapse than others due to their internal structure and mechanical properties.





Figure 2: The 100 m section of ring fault does not have a constant vertical attitude, contrary to the findings of many analogue models of caldera formation. Several inclined sheets are observed meeting the fault and either arresting or deflecting along the fault.

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# Three-dimensional geometry of Las Cañadas caldera phonolitic dykes

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The Las Cañadas caldera (Tenerife) is an overlapping collapse caldera originated through multiple vertical collapse episodes occurred during the construction of the upper part of Las Cañadas edifice (Martí and Gudmundsson, 2000). Three long-term ( $\geq 200$  ka) cycles of phonolitic explosive activity, each culminating with a caldera collapse episode, have been identified in the upper part of Las Cañadas edifice, where the focus of felsic volcanism migrated from west to east.

Different families of phonolitic dykes, including cone-sheets, radial and concentric dykes, are well exposed along the caldera wall. Their diverse cross cutting relationships suggest that several intrusion episodes from differently located magmatic sources occurred during the construction of the upper part of Las Cañadas edifice (Martí et al., 1994).

We conducted a field study in which we measured strike, dip and thickness of 374 sheet intrusions of phonolitic composition. The results of stress fields were obtained by solving the equations for 3D linear elasticity for each geometric configuration and set of boundary conditions. The solutions were calculated numeri-

cally with commercial software COMSOL using the finite element numerical method.

These results permitted to reproduce the 3D geometries of the different families of dykes that we used to identify the location, depth, and size of their magmatic sources. The results obtained permitted to identify different shallow magma chambers, corresponding to the different phonologic cycles identified from the stratigraphy of Las Cañadas deposits.

This confirms that the formation of the overlapping Las Cañadas collapse caldera was related to migration of the associated magma chambers.

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# The effect of sill emplacement on petroleum systems

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A petroleum system is defined by 5 elements, (1) a source rock, where the organic material by thermal transformation generates oil and gas, (2) a carrier bed, that offers a migration pathway for oil and gas out of the source rock and into a reservoir, (3) a trap, that focuses the migration of oil and gas into accumulation, (4) a reservoir rock, in which oil and gas can accumulate, and (5) a seal rock that keeps the oil and gas from migrating out of the reservoir. Magmatic intrusions, such as sills and dykes, may affect or be involved in all the elements that make up a petroleum system.

The thermal effect of the emplacement of single sills and sill complexes in a sedimentary basin was analysed by Fjeldskaar et al. (2008). The results showed that the emplacement of sill complexes is likely to greatly affect the temperature history in a basin, and thereby the transformation ratio of organic matter into hydrocarbons in a source rock. They also showed that the temperature increase of sill complexes affect a large area, and may lead to increased source rock maturation and hydrocarbon generation at shallower depths than for a basin without sills.

During emplacement, the hot magma comes in contact with much cooler host rocks often containing pore fluids. This normally gives rise to the formation of a glassy margin/chilled selvage at the margin of the sill (Fig. 1). If not broken, this

margin can act as a low-permeability seal. In addition, contact-metamorphism reduces the grain size of the sill and host rocks. These processes may contribute to changes in migration pathways for oil and gas. Depending on the status of the margin (broken or unbroken) the migration may go into, through or along the margins of the sill. This implies that the sill margin may become effective traps for migrating hydrocarbons.



**Figure 1: Glassy margins at the contacts between a hyaloclastic host rock and a dyke in Hengill area, southwest Iceland.**



The key properties of reservoirs are porosity and permeability. High porosity indicates large storage capacity, and high permeability (made up of an interconnected system of pores and fractures) implies that oil and gas can easily flow out of the reservoir during production.

Thick sills are characterized by vertical to sub-vertical columnar joints and horizontal to sub-horizontal joints (Fig. 2), so the fracture systems developing within the sills are normally very well interconnected. The fracture frequency is often high, so that the fracture-related porosity may also be high. If the glassy margin at the upper contact of the sill is intact while the lower one is broken, then sills may act as excellent fractured reservoirs.



**Figure 2:** Sill reservoir analogue at Reynisfjara, south Iceland. The intrusion has numerous vertical columnar joints and horizontal joints, giving it the ideal reservoir properties of high permeability and porosity.

Sills may also contribute to reservoir formation in other ways. Results from numerical models show that during emplacement, the sill-induced stresses may lead to formation of fractured reservoirs in stiff layers/units in the overburden, relatively far away from the sill itself (Gudmundsson and Løtveit, 2012).

If the glassy margin of the lower contact is intact, then the sill may act as a seal. Many examples of how sills may act as seals are provided by Schutter (2003a, b).

There are several examples of petroleum production from thick sills worldwide, however, on the Norwegian shelf this is regarded a new petroleum play.

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Rock fractures play a major role in many geological processes, such as plate tectonics, earthquakes, volcanic eruptions and fluid transport in the earth's crust. The present volume contains the abstracts of all presentations of the symposium „Rock Fractures in Geological Processes“, held on 26–27 November 2013 in London honouring the 60th birthday of Agust Gudmundsson, chair in Structural Geology, Royal Holloway University of London, a leading expert in the field and author of a well known text book of the same title. The symposium covered all topics related to fractures in the earth's crust, e.g., crustal stresses, rock mechanical properties, field analysis of fractures – from joints and faults to mineral veins and dykes –, analytical, analogue and numerical models of fractures and related fluid transport, as well as the activity of faults and volcanoes including calderas, and economic aspects such as exploration and exploitation of hydrocarbons and geothermal energy.



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