Interdisciplinary exploration of the lithosphere

Without localised deformation in the Earth's lithosphere, there would be no plate tectonics. **Professors Laurent Jolivet** and **Evgueni Burov** are working to better understand this process of strain localisation by uniting disparate scientific communities. Here, they describe the goals and challenges of their work, and the importance of combining approaches

Could you outline the objectives of the 'Rheology of the continental lithosphere, a geological, experimental and numerical approach' (RHEOLITH) project?

LJ&EB: RHEOLITH is a multidisciplinary project focused on the mechanisms controlling localised deformation in the continental lithosphere at different time scales. Plate tectonics and continental drift have shaped the Earth's surface for at least the last 2 billion years and this intense activity continues today with rapid displacements (at an order of 1-15 cm/year) of effectively rigid plates above a viscous mantle and intense, often seismogenic deformation where the plates interact.

This process leads to formation and propagation of mega-faults and the mountain belt formation in the long term (several tens of millions of years), volcanic and magmatic events at intermediate term and earthquakes in the short term. Such fast displacements of nearly unreformed plates over thousands of kilometres require that the deformation is localised along plate boundaries and not distributed over large surfaces. Without specific physical processes that lead to strain localisation, plate tectonics would not exist. Despite its importance, this area is still poorly understood. An actively debated topic, it has been approached by a range of specialists using different spatial scales and time constants of varying complexity.

RHEOLITH is coordinated by the Institute of Earth Sciences of Orléans (ISTO) and the Institute of Earth Sciences Paris (ISTEP). What role do these establishments play, and how is effective collaboration facilitated?

LJ: ISTO hosts myself as Principal Investigator (PI) of the project and is charged with field data acquisition, radiometric dating and experimental deformation. ISTEP in Paris hosts co-PI Professor Evgueni Burov, and leads the multi-physical numerical modelling part of the project. Close cooperation of the two teams is facilitated by the long history of scientific and personal relations between them.

How will RHEOLITH combine different approaches (geological, experimental and numerical) to better understand lithosphere behaviour?

LJ&EB: Our basic strategy is to use these three approaches on the same natural objects and analyse the outcomes. Multiphysical (initially thermo-mechanical) numerical modelling has a very important role – it serves as a tool for validation and interpretation of geophysical and laboratory data and geological observations, ensuring that scale transfer from the lab to the lithosphere is accurate and physically consistent. For example, we have started to conduct virtual rock-mechanics experiments, that is, numerically model the same type of experiments we conduct in the lab with Paterson or Griggs apparatus. The parameters will then be transferred from scale to scale, with the final goal to produce lithosphere-scale deformation models matching the observations. The problem is that the lithosphere's complexity means small-scale mechanisms cannot simply be scaled up.

The famous eclogite and blueschists of Syros island (Cyclades, Greece) record the pressure (~20 kbar) and temperature (~500 °C) conditions of the deep parts of subduction zones, along the plates' interface where strain occurs.

How does the continental lithosphere vary across the globe and why do these variations occur?

LJ&EB: The continental lithosphere varies greatly from one place to another because of its complex geological history. Its low density and generally substantial mechanical strength limits its subduction so large continental domains continually stay at the Earth's surface, thus providing a very long record of geological history. Phases of crustal thinning take place in between those of mountain belt formation. Each of these events has led to the creation of different rock types that form variably sized units, from a few metres to entire massifs such as the Alps.

Why does this make it difficult to comprehend deformation processes?

LJ&EB: The rheology (study of the flow of matter) of these rocks differ due to their mineralogy, internal structure and many other factors such as water fugacity (vapour pressure), and this has consequences for the crust's rheology. This complexity makes the continental lithosphere a difficult object to study; however, as we live on it, we have no choice but to cope with its intricacy. Fast computers, new numerical methods and sophisticated geophysical techniques make the challenge more approachable – the resolution of numerical models and geophysical data are getting closer to geological observations than ever before.

RHEOLITH's three-pronged approach

- Direct observations and characterisation of deformed domains (shear zones) in terms of their geometry, kinematic history, pressure and temperature
- Experimental study of the mechanical characteristics of rocks involved in the studied shear zones
- Numerical modelling of the processes governing strain localisation at different scales of space and time

Tectonic **evolution**

The rheology of Earth's outer surface is an important and intensely debated topic among Earth scientists. A project coordinated by the **University of Orléans** and **Université Pierre et Marie Curie**, Paris, France, is reconciling various approaches to derive a solution to this long-standing geological quandary

THE LITHOSPHERE IS a rigid outer layer of the Earth that remains mechanically strong over geological time spans. Of the planet's three main layers – the Core, the mantle and the crust – the lithosphere includes the crust and upper section of the mantle, and is around 100 km thick. Mechanical lithosphere includes strong layers of crust and outermost mantle, capable of maintaining and transferring high tectonic stresses. Continually moving, albeit very slowly, the lithosphere is broken into large segments called tectonic plates. The brittleness and elasticity of the uppermost crust and mantle causes earthquakes by faulting, and in the longer-term lithospheric deformation, generally viscous-elastic or viscous-elastic-plastic, leads to the formation of mountain ranges along converging plate boundaries and rift basins or ridges along the diverging boundaries.

Better understanding the lithosphere's rheology (ie. the ensemble of physical properties that define how the lithosphere deforms under imposed stresses or vice-versa) is essential to characterise the events leading to earthquakes, but also to relate short- (earthquakes) and long-term (mountains) deformation regimes.

Professors Laurent Jolivet and Evgueni Burov, leading researchers in the field of tectonics and Principal Investigators (PIs) of the 'Rheology of the continental lithosphere: a geological, experimental and numerical approach' (RHEOLITH) project, are helping to bridge important knowledge and methodological gaps in the field. By bringing together different disciplines, and combining their observations in multi-physical, multi-scale numerical models, RHEOLITH hopes to shed further light on lithosphere deformation and answer fundamental, unresolved questions in geology and the Earth sciences in general.

THE SUBJECT OF DEBATE

Continental lithosphere deformation is approached, and thus perceived, differently by various scientific communities: "From an earthquake that may last seconds to the formation of mountain belts over 40 million years, the jump in timescale is tremendous. From the deformation of a 1 cm sample in the lab, to the San Andreas Fault that cuts the North American Plate along some 800 km, there is little in common and, so far, very little work has been done to reconcile these scales," Jolivet explains.

Methodological differences also exist between the fields. Geologists are familiar with complex, natural objects. Using a variety of observational techniques, they can describe the evolution of structures in terms of geometry, time, temperature and pressure conditions, but can only offer conceptual models. Their data are also often quite segmented, or incomplete, since a large part of deep lithosphere processes cannot be constrained from direct observations. Experimentalists on the other hand can capably measure the 'mechanical properties' of the rocks in the lab, but stumble when it comes to the behaviour of rocks in nature because the attainable laboratory conditions are strongly different from the natural ones. Specifically, ultra-slow geological deformation cannot be reproduced experimentally, and there is no certainty that the same deformation mechanisms are activated at human/laboratory time scale (few months) and geological time scales (millions of years). Finally, physical numerical modellers are able to choose scales of time and space, and can incorporate multiple physical processes and parameters in state-of-the-art numerical models. However, the resolution of geological-scale models is still low compared to geological observations while a large part of 'mesoscale' information that is crucial for building physically consistent models is missing.

SHEAR ZONES

Launched in August 2012, RHEOLITH involves studying exhumed, crustal-scale, shear zones (the deep level equivalent of a fault). The project considers the continental lithosphere in its natural complexity, and as such, will be studied in its natural context, including large Aegean detachments and partially molten rocks in Norway. Shear zones will be treated in different contexts and on a wide range of scales, from the laboratory to the lithosphere, with focus on deformation localisation.

To facilitate this, the team installed a new argon dating lab at the Institute of Earth Sciences of Orléans (ISTO), with three spectrometers for *in situ* and step-heating radiometric dating. The lab will be used for dating along strain gradients. "Radiometric ages using the $^{40}Ar/^{39}Ar$ method are not only controlled by the closure temperature, but also by the timing of deformation itself, and we can observe age gradients across shear zones," Jolivet explains. The aim is to obtain dense transects of ages across the shear zones; an approach that will quantify strain localisation rates and overcome local artefacts. The team is also installing a new high-pressure press (a Griggs apparatus) with an original design that

INTELLIGENCE

RHEOLITH

RHEOLOGY OF THE CONTINENTAL LITHOSPHERE, A GEOLOGICAL, EXPERIMENTAL AND NUMERICAL APPROACH

OBJECTIVES

To link small-and large-scale rheological parameters to better understand strain localisation in the continental lithosphere based on a threefold approach: field characterisation of natural shear zones; experimental acquisition of rheological parameters; and numerical modelling.

KEY COLLABORATORS

Professor Holger Stünitz, University of Tromsö, Norway • **Dr Alexandre Schubnel**, Ecole Normale Supérieure, France • **Professor Claudio Faccenna**, University Roma Tre, Italy • **Professor Taras Gerya**, ETH Zürich, Switzerland • **Professor Torgeir Andersen**, University of Oslo, Norway • **Professor Brian Evans**, MIT, USA • **Professor Anthony Watts**, University of Oxford, UK

PARTNERS

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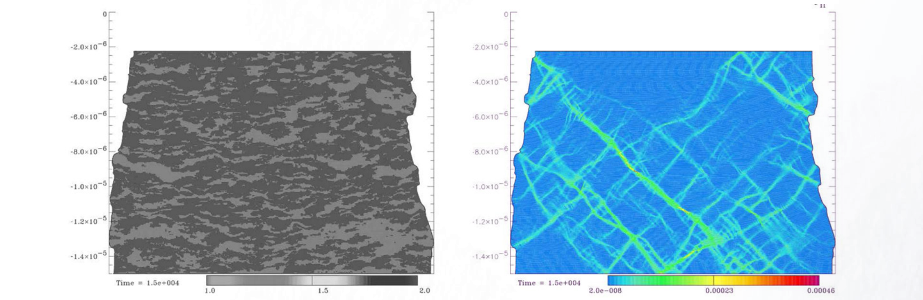
LAURENT JOLIVET obtained his PhD in 1984 at UPMC in Paris. He then spent 11 years at Ecole Normale Supérieure, Paris, three at Université de Cergy-Pontoise, and another 11 at UPMC. In 2009 he moved to the University of Orléans. He was awarded the Stephan Müller medal of the European Geosciences Union in 2011.

EVGUENI BUROV obtained his PhD in 1990 at Institute of Physics of the Earth in Moscow, Russia. He then spent one year at the University of Leeds, UK, four years at Institute of Physics of the Earth of Paris (IPGP), three years at BRGM (French Geological Survey) and then moved to UPMC. He is an elected member of the European Academy of Science (Academia Europaea).



Numerical modelling of rock sample deformation at ISTEP with conditions similar to those of the Paterson press in use at ISTO.

will allow measuring rheological parameters of rocks in the lab.

At the core of the project are two important issues: the ductile-brittle transition of lithospheric rock, and the influence of partial melting on crust deformation. The ductile-brittle transition is very important in subduction zones, being, according to some views, the deepest part of the zone where large earthquakes nucleate. In order to understand what happens at these zones, the team is studying rocks from the plate interface taken from a fossilised accretionary wedge in Japan.

Partial melting – another vital geological phenomenon – can decrease rock resistance and plays a key role in strain delocalisation. Localised partial melting tends to confine deformation, while generalised melting will distribute it over large areas, causing the collapse of mountain belts. "We are studying this through the behaviour of granitic plutons, derived from partial melting of the crust, and their relation to large-scale detachments in the Cyclades," illuminates Jolivet.

MAKING HEADWAY

The project has made exceptional progress so far. Field work is in its advanced stages and the team has produced new geological and structural maps based on this. They are currently studying shear zones for argon dating in Greece and Corsica; sampling is underway and laboratory processing is due to start soon.

Partial melting experiments have also been completed on natural rocks and the first results are already available. Investigations have shown that partial melting in the Norwegian Caledonides begins near the peak of pressure in the subduction channel, with drastic rheological consequences. Parallel work has elucidated a possible mechanism for the transition between aseismic and seismic deformation along the plate interface in subduction zones. Sedimentary rocks deformed under controlled temperature conditions were shown to display behaviour characteristic of earthquakes, while samples deformed at ambient temperature did not show any instability. The team believes a smectite to illite reaction underlies these instabilities. Further analysis of natural deformation by the researchers has revealed a novel mode, active at low temperatures in the presence of fluid where plasticity is not yet active.

The Argon lab in the making. These machines will allow the dating of rock minerals and their deformation with the $^{40}Ar/^{39}Ar$ method.

These advances are not restricted to the field; progress has also been made in numerical modelling experiments. In the first phase of the project, the team acquired supercomputing infrastructure, analysed primary data and refined their techniques. Particularly exciting advances include the development of fully 3D high-resolution models, a micro-scale modelling approach allowing the simulation of laboratory experiments and a novel numerical approach accounting for fluid percolation.

NUMERICAL PHYSICAL MODELLING

Accounting for complex thermomechanical and thermodynamic behaviours and complex 2D and 3D geometries of geological structures at different time scales is both a computational and fundamental theoretical challenge. The team is developing and adopting numerical algorithms for modelling lithosphere and rock deformation at different time and spatial scales (from rock sample to lithosphere scales, from milliseconds to millions of years). This task presents a particular challenge provided that none of the existing solid-state deformation codes is capable of handling, even in theory, the numerical resolutions of billions of grid elements that would be adequate to the problem.

ADAPTING RHEOLOGICAL MODELS

Looking ahead, RHEOLITH will link each tectonic process with relevant scale-dependent rheological parameters. This will ultimately lead to a generalised preliminary rheology model set for the lithosphere (PReMSL), which will cover the entire time and spatial range of deformation – an exciting prospect for all in the field.

As the project continues, it will make significant contributions to understanding how plate tectonics have developed on Earth. In doing so, scientists will be able to understand how and why fast displacements, such as those that take place during earthquakes, can occur – a finding with implications far beyond geology.