

Mapping mantle's past

DR ALIK ISMAIL-ZADEH

Investigating how the past has shaped the present, research led by **Dr Alik Ismail-Zadeh** is exploring how understanding behaviour of Earth's crust and lithosphere could help predict geohazards



How did you arrive at your current project and what principal questions are you seeking to answer?

In the 1990s, I was analysing sedimentary basins with a view to understanding how basin evolution is complicated by deformations that are induced by salt dynamics. Having found that there was a deficit of efficient tools for dynamically reconstructing the evolution of these basins, together with two geologists – Chris Talbot of Uppsala University, Sweden and Yuri Volozh of the Russian Academy of Sciences (RAS), Moscow, I developed a backward advection tool for the dynamic restoration of salt-bearing basin evolution.

I later realised that, aside from this backward advection tool, there was no existing efficient methodology for studying the evolution of deeper Earth structures in the past. Although mantle dynamics is more complicated than salt tectonics, interestingly, salt deposits are less dense and ductile compared to brittle sediments of salt's overburden – it behaves like the asthenosphere and its overburden behaves like the lithosphere. Therefore, the methodology for data assimilation, which we developed for dynamic reconstruction of salt-bearing basins, could be applied to modelling mantle dynamics.

I shared this idea with Dr Jerry Schubert, a geodynamicist and planetary scientist at the University of California, Los Angeles (UCLA). He asked for convincing arguments that thermally diffused structures of the Earth's mantle could be restored mathematically, even though diffusion is an irreversible physical process. In

collaboration with Russian mathematicians Alexander Korotkii and Igor Tsepelev, RAS, Yekaterinburg, and Jerry Schubert we published a series of papers presenting methods for data assimilation and their applications to restoration of thermal (synthetic) structures.

The question remaining was whether we could apply the techniques to observed structures in the Earth in order to analyse the history of mantle dynamics – the fundamental question we are asking with a goal to better understand the evolution of descending lithosphere in two distinct geological environments.

Are you analysing specific processes?

We have been analysing mantle flow in the geological past and the evolution of the thermal structures in the mantle as well as strain-stress evolution. The processes associated with lithosphere subduction and mantle upwelling have been our primary subjects for study.

Why have you decided to focus specifically on the evolution of descending lithospheric slabs?

As the lithosphere moves away from an oceanic ridge, it cools and thickens. Once it becomes sufficiently dense compared to the underlying mantle rocks, it bends and begins a descent into the hot mantle due to gravitational instability. The downward buoyancy forces promote the sinking of the lithosphere, but elastic, viscous and frictional forces resist the descent. The combination of these forces produces shear stresses high enough to cause earthquakes. Oceanic trenches are the sites of the world's largest earthquakes. In fact the catastrophic earthquake in Tohoku, Japan, on 11 March 2011, occurred along the descending lithosphere.

Which locations are you focusing on?

We seek to understand how the active Pacific and Philippine descending slabs evolved with time. We are also asking what happens to the descending slabs at the end of the Wilson cycle – ie. at the closure of an oceanic basin – and in the zones of continent-continent collision. A typical geological domain that allows the study of this process is the south-eastern (SE) Carpathian Mountains (the Vrancea region), where large earthquakes occur several times a century and shake central and eastern parts of Europe.

To understand seismic processes, it is not sufficient to analyse only an earthquake rupture itself. It is desirable to determine the reasons of strain-stress localisation at the network of respective fault planes, which are linked to lithosphere dynamics and hence are rooted in the past. Therefore, we started from the analysis of dynamic evolution of a descending lithosphere and its strain-stress states.

What methods were used to assimilate the data?

In geodynamics, data assimilation can be defined as the incorporation of present observations on specific geophysical quantities (eg. velocity, temperature) in an explicit mantle dynamic model in order to determine approximate values of the quantities in the geological past, minimising the discrepancy between the observations and the solution to the model.

What have been the main challenges you have encountered, and how have they been overcome?

A mathematical problem of the reconstruction of the Earth's dynamics and of thermal structures in the mantle belongs to a class of ill-posed inverse problems and the main challenge was to solve these. At the beginning of the 21st Century, only backward advection methods were in use. In the last decade, several other data assimilation techniques – which account for thermal diffusion – have been developed: sequential filtering, variational (VAR) or adjoint and quasi-reversibility (QRV) methods.

The VAR method has a high degree of accuracy in determination of the values of geophysical quantities in the past, but suffers from noise generation. The QRV method has proven to be well suited for assimilation of data related to mantle dynamics. It is less accurate than VAR but can suppress the noise. Thus VAR and QRV methods as well as backward advection have been employed in the project.

Does your research draw on any previous studies or theories?

Our research is based on contributions from many mathematicians and geoscientists, notably Jacques Hadamard, a French mathematician who conceived the idea of well- (and ill-) posed problems in the theory

of partial differential equations, which provided a mathematical background for solving inverse problems.

How does your project differ from previous work?

Our project is built on the mathematical and geophysical foundations laid by previous research. Our aim was to develop further mathematical and computational topics related to data assimilation, and to apply these techniques to study the geodynamic evolution of mantle structures. The project has also been strengthened by its interdisciplinary and international nature: geoscientists and mathematicians from Germany, Japan, Russia, and the US have contributed to its realisation.

What have you learned about conventional perceptions of mantle convection and subduction zones, particularly during your studies of the Pacific plate near the Japanese islands?

Using assimilation techniques, we developed a dynamical model combining available data to unravel the dynamics of the Earth's interior in the past. The principal finding is that the anomalous hot mantle beneath the Pacific plate penetrated through the descending part of the plate around 40+ million years ago and contributed to the development of the Japan Sea (back-arc basin). This result may have important implications for back-arc spreading, breakoff or tearing of descending slabs, and a geochemical mixing between the rocks of the deep and shallow mantle.

Has your team created any novel models?

Yes we have. The models developed in the framework of this project can be divided into three types: models of present instantaneous mantle flow, temperature, and strain-stress; direct numerical models (forward in time), which have been used basically as auxiliary models for testing; and inverse retrospective numerical models (backward in time). The basic emphasis of the project has been placed on the third type of the models, as they are based on data assimilation.

What major outcomes and applications do you expect from your findings?

The major scientific outcomes of the project are theoretical, and contribute to understanding of lithosphere subduction beneath Japan as well as of relic lithosphere sinking beneath the SE-Carpathians. The results can help improve understanding of the strain-stress evolution in the region.

Further outcomes of the project are methodological – we have developed techniques that could be used in geodynamic data assimilation research.

Do you plan to focus on any other subduction zones in your future work?

I would be interested in conducting research in any other subduction zones where vast geophysical, geological and geodetic data are available. Perhaps the next step would be to study the post-Eocene mantle evolution beneath the Tibet-Himalayan region – another major earthquake-prone area with a complicated geological history.

Lithosphere evolution and earthquakes

An innovative group at the **Karlsruhe Institute of Technology** in Germany and the **Russian Academy of Sciences** is developing new methods to analyse the evolution of the mantle and descending lithosphere plates. These tools will help us to better understand the processes in the deep Earth that lead to earthquakes

IT MAY BE hard to believe, but the ground beneath our feet is constantly moving. The enormous pieces of rock that constitute the Earth's crust are in a state of continual, albeit very slow, motion – a movement we remain unaware of until the rock pieces grate past each other or collide. When this occurs, ripples of energy are released in the form of seismic waves resulting in earthquakes of varying magnitude. Some are a barely detectable tremble, while others are disastrous, causing major damage and death.

One example of a mammoth earthquake is that which hit Japan in 2011. Now recorded as the fifth most powerful earthquake of the last century, the quake measured 9.0 on the Richter magnitude scale and struck just 81 miles east of Sendai, inducing a giant tsunami that ravaged the eastern part of the country, destroying homes and drowning inhabitants. The quake was so powerful, and resulted in such far-reaching tsunami waves, that its impact extended beyond Sendai to Fukushima, 150 miles north of Tokyo. Here tsunami damaged the cooling system of the nuclear power plant, causing a dangerous radiation leak, which forced a mass evacuation. The National Policy Agency of Japan reported on 10 July 2013 the quake and the tsunami to have claimed the lives of 18,550 people. This massive loss of life exposed our limited understanding of these natural hazards and related disaster risks and calls for further research.

To better understand the manifestation of earthquakes, greater knowledge is required of how the Earth's crust and lithosphere movements develop, how those slabs of rock came to be what they are today and why they behave in the way they do. If the history of these rocks can be mapped, we should, in theory, be able to understand how an earthquake

develops over time and hopefully predict them with higher degrees of accuracy.

LOOKING BACK ON DATA

For over 20 years, Dr Alik Ismail-Zadeh has been searching for a method to analyse and understand the geological evolution of the crust and mantle. He has worked collaboratively with internationally acclaimed scientists and his research group, based at the Karlsruhe Institute of Technology in Germany and at the Russian Academy of Sciences in Russia (Moscow and Yekaterinburg), and is now specifically interested in the evolution of descending lithospheric slabs – the outermost, and therefore hardest, layer of the Earth. It sits on top of the hotter 'liquid' phase of the upper mantle, known as the asthenosphere.

The Earth's lithosphere is comprised of huge plates of rocks (or lithosphere plates), which are in constant motion. As these plates come into close contact with one another, convergent boundaries are created, where one plate moves underneath the other, sinking into the asthenosphere mantle beneath. This process is called subduction and can be deemed 'active' – meaning the plate is essentially forced to descend by 'plate push' – or 'passive' ('gravitational') – meaning that the gravitational forces acting on the plate are driving its movement downwards ('plate pull'). Areas rich in subduction are found to experience the most earthquakes.

Ismail-Zadeh's team has utilised the SE-Carpathians and Japanese island locations to study these different types of lithosphere decent. Both of the areas experience big earthquakes and tectonic stress localisation. However, whereas the Pacific plate beneath the Japanese islands is reported to experience active subduction, the movement in the relic

Vrancea slab under the SE-Carpathians has a gravitational cause.

By using the vast geophysical, geological and geodetic data available for these two regions, the group has attempted to develop unique 3D data-assimilation codes capable of mapping the thermal changes in the regions and assimilating the previous observations accounting for geological history. The aim of the researchers was to use these models to identify any patterns in the plate behaviour, thereby shedding light on their evolution trajectory.

CREATING NEW METHODS

In order to create thermal models of the mantle beneath the Japanese islands and numerical models of the evolution of the lithosphere subduction, Ismail-Zadeh's group first needed to develop a mathematical technique which could

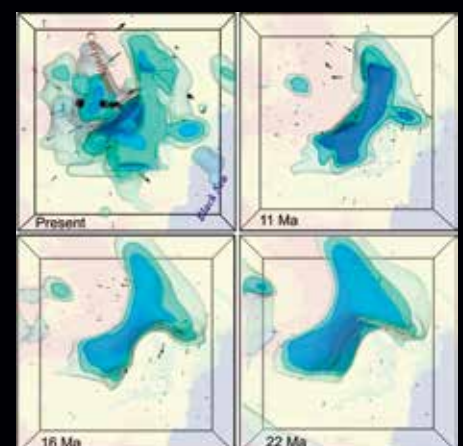


Figure 1. Snapshots of the evolution of the lithospheric slab (blue-shaded areas) beneath the Southeast Carpathians (view from above) © I Tsepelev

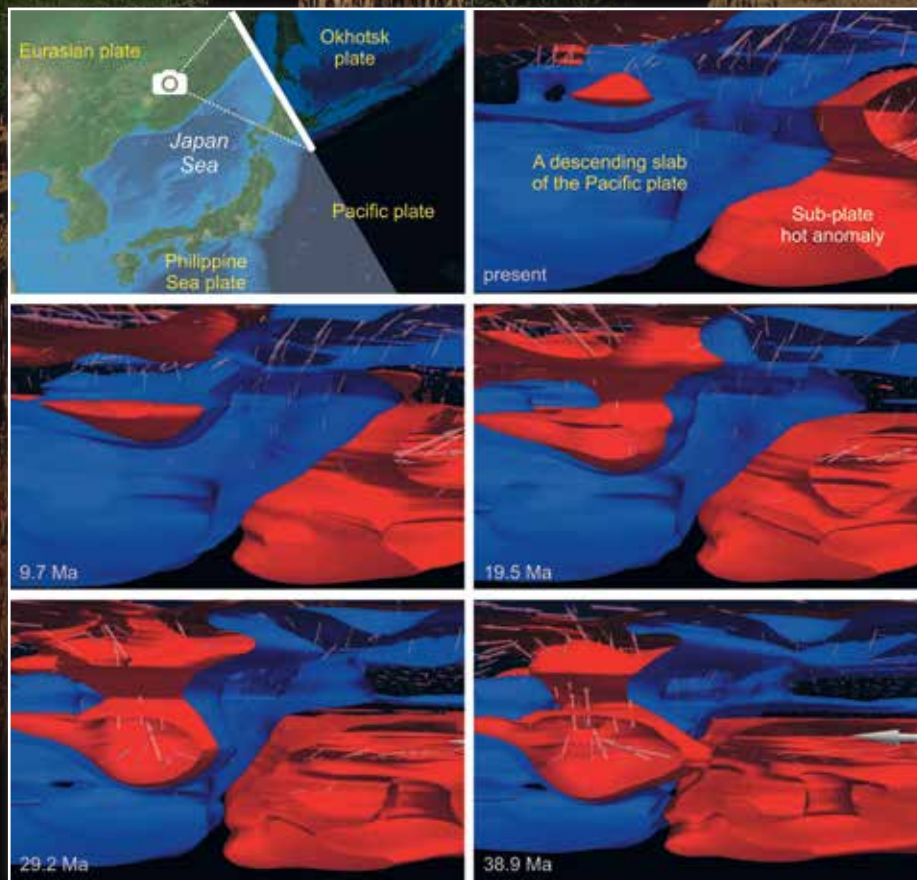


Figure 2. Snapshots of the evolution of the lithospheric slab (blue) and the hot mantle (red) beneath the Pacific lithosphere (side view from southwest) © A Helfrich-Schkarbanenko

deal with ill-posed (unstable) thermodynamical problems. By basing their coding on the finite element/finite difference and finite volume methods, the researchers were able to develop two computer codes to combat these inverse problems, which could then be applied within their 3D models.

By using these models the team has taken the present temperature model derived from P-wave seismic tomography data for the mantle beneath SE-Carpathians and assimilated it into the geological past (around 20 million years ago). There are two slab portions underneath Southeast-Carpathians, one of which is still showing a present descent. Using their 3D models the researchers have suggested that previously these two slabs were just one (Figure 1). This suggestion was made based upon their observations that the rock above 60 km is concave in nature and that the rock below 60 km exhibits a convex bend. Moreover, they have hypothesised that the slab bending back and forth resulted in an energy accumulation and that at depth of 220 km it eventually divided into two. The release of energy this would have caused could have generated some of the larger earthquakes experienced in the area. The scientists have also suggested that earthquakes of lower magnitude in the region are likely to be a result of the rock melting and embrittlement.

Recent seismic data have shown that there is an area of low velocity/high temperature beneath the subducting Pacific plate near Japan at the

depth of about 400 km. This is rather unusual and has raised questions as to how it got there and what impact it could have. By using their models to assimilate geological, geodetic and geophysical data back into the past 40 million years, Ismail-Zadeh's group has hypothesised that a part of hot mantle penetrated through the subducting Pacific slab into the mantle above the slab and contributed to the opening of the Japan Sea. Another part of the hot mantle migrated up beneath the Pacific lithosphere, and the seismically-detected hot anomaly is a remnant of this old upwelling (Figure 2).

APPLYING THE TOOLS

Ismail-Zadeh's research has led to the development of novel and effective methods for geodynamical data assimilation. The assimilation models created by the group will aid further research into the development, current behaviour and possible evolution of descending lithosphere slabs and mantle upwellings. So far the models have been successfully applied to observations from two key geological areas, as demonstrated by their proposed hypothesis for the abnormal thermal reading at the subducting Pacific plate.

It may be that the behavioural patterns the researchers have unearthed are common to other subduction spots meaning that these project results can open new perspectives for the study of complex interaction between the descending lithosphere, sub-lithospheric mantle and mantle wedge in a range of locations.

INTELLIGENCE

EVOLUTION OF DESCENDING LITHOSPHERIC SLABS AS INFERRED FROM ASSIMILATION OF GEOPHYSICAL, GEOLOGICAL AND GEODETIC DATA

OBJECTIVES

- To understand the evolution of descending lithosphere and other thermal structures in the mantle beneath two distinct geological environments: the SE-Carpathians and the Japanese islands
- To develop a novel approach in computational geodynamics based on assimilation of geophysical, geological and geodetic observations into the past
- To study the thermal, structural and stress-strain evolution of the regional lithosphere using developed numerical models constrained by observations

KEY COLLABORATORS

Gerald Schubert, UCLA, USA

Satoru Honda, University of Tokyo, Japan

Igor Tsepelev; Alexander Korotkii, Russian Academy of Sciences

FUNDING

Deutsche Forschungsgemeinschaft (German Research Foundation) Project IS-203/1-1

CONTACT

Dr Alik Ismail-Zadeh
Project Director

Karlsruhe Institute of Technology
Institute of Applied Geosciences
Adenauerring 20b, Geb 50 40
76131 Karlsruhe
Germany

T +49 721 6084 4610
E alik.ismail-zadeh@kit.edu

ALIK ISMAIL-ZADEH is a senior scientist at the Karlsruhe Institute of Technology, Germany; chief scientist at the Russian Academy of Sciences, Moscow; and visiting research professor at Institut de Physique du Globe, Paris, France. His scientific interests cover studies of dynamics of the Earth's crust and upper mantle and their surface manifestations (including geohazards) through multidisciplinary synthesis and theoretical/computational analysis. He is an author/co-author of over 100 peer-reviewed papers and four books.

