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HUMBOLDT KOLLEG – 2016

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THE FACULTY OF MINES – İHSAN KETİN CONFERENCE HALL

10 – 12 MARCH 2016

Advances in Earthquake Seismology and Geodynamic Modeling

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Welcome – *Concept of the Humboldt Kolleg*

An accurate knowledge of the dynamic forces behind the movement of plates is vitally essential to better constrain the processes (*e.g.,* mountain building, convergence of the plates, etc.) shaping our planet throughout its evolution at the regional and global scale. As it is widely known that our planet, *Earth*, undergoes a strong deformation along extended plate boundary zones, which therefore play a key role for elucidating the force balances and rheologies governing the lithospheric-scale tectonics.

Two primary models of deformation are often used to explain distributed lithospheric deformation in continental areas. The initial one requires a complete kinematic coupling of the crust and mantle lithosphere resulting in vertically coherent deformation. The latter type of model involving a low-viscosity layer in the mid- or lower crust assumes a decoupling between the upper crustal deformation and the mantle. This model was tested first in laboratory conditions within a setup where mid-crustal flow of 10-15 km thickness are considered under viscous conditions in order to understand the response of material within a layer of low viscosity to the extensional tectonics of Basin and Range province. Later, in a similar fashion, the idea of weak lower crust was proposed to explain the uplift and topographic variations observed in the Tibetan Plateau.

Within the framework of “**the Humboldt Kolleg**”, our main aim is to gather the information of rheology and density properties that could be hinted at mainly various seismological observations validated with geodynamic studies in order to enhance our understanding concerning time and spatial evolution of the continents. In long perspective, an accurate knowledge of the processes shaping the continental crust and/or mantle can provide crucial clues for certain societal issues, for instance the further evolution of seismic cycles, climatologic variations as such, that are considered to have a great impact on the evolution of life in long run. New strategies in earth sciences require merging different datasets and perspectives for further interpretation. Thus, during “**the Humboldt Kolleg**”, participants from the fields of geophysics, geology, seismology, geodynamics and active tectonics will find a chance to collaborate together and discuss on the consistencies between geophysical observations, proposed models, and numerical simulations with several coupled-examples from diverse parts of the Earth including eastern Mediterranean, Anatolia, Central Asia, North America, and Europe.

We would like to increase our international cooperation and hope that participants will enjoy the benefits of the Humboldt Kolleg gathering. We sincerely believe that friendly atmosphere of the Humboldt Kolleg will eventually help to initiate future joint studies for the mutual benefits.

Tuncay Taymaz *(Chairman*)
Tuna Eken and Seda Yolsal-Çevikbilen (*LOC Executive Secretaries*)

notes

Alexander von Humboldt (by Henry William Pickersgill, 1831)

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Alexander von Humboldt – *About the Foundation*

Alexander von Humboldt (1769-1859) was a nature researcher and explorer, universal genius and cosmopolitan, scientist and patron. His lengthy Latin American journey from 1799 to 1804 was celebrated as the second scientific discovery of South America. Members of natural science disciplines such as physical geography, climatology, ecology or oceanography see Humboldt as their founder. The masterpiece of his advanced years, the five-volume "*Cosmos. Draft of a Physical Description of the World*" has remained unique in its comprehensive approach.

Alexander von Humboldt not only invested his inheritance in his own studies but also selflessly sponsored other young scholars and talents, among them Justus von Liebig and Felix Mendelssohn-Bartholdy.

Selected Literature

Alexander von Humboldts Reise durchs Baltikum nach Rußland und Sibirien 1829, aufgezeichnet von Hanno Beck, 2. Verb. Aufl. Stuttgart: Thienemann 1984.

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Gebauer, Alfred: **Alexander von Humboldt. Forschungsreisender, Geograph, Naturforscher,** Berlin: Stapp 1987.

Meyer-Abich, Adolf: **Alexander von Humboldt,** Hamburg: Rowohlt 1967 (rm 131).

McIntyre, Loren A.: **Die amerikanische Reise. Auf den Spuren Alexander von Humboldts,** 2nd. Edition, Hamburg: Gruner + Jahr 1986.

de Terra, Helmut: **Alexander von Humboldt und seine Zeit,** 2. Edition, Wiesbaden: Brockhaus 1959.

Slonimski, Chaim Selig: **"Zur Freiheit bestimmt. Alexander von Humboldt – eine hebräische Lebensbeschreibung",** including an essay about **"Alexander von Humboldt und die Juden" by Peter Honigmann, edited by Kurt-Jürgen Maaß,** Bonn: Bouvier Verlag 1997.

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Alexander von Humboldt Foundation – The Roots

Alexander von Humboldt (1769-1859) was a discoverer and cosmopolitan, a fighter for the freedom of research, a humanist, and a patron of excellent academic talent. Shortly after his death, the Alexander von Humbodt Foundation for Nature Research and Travel was established in 1860. Until it lost its endowment captial in the inflation of 1923, it essentially provided support for German scientists setting off on research journeys to other countries.The objective was to use international exchange in the spirit of Humboldt to overcome boundaries and promote universal understanding.

A new **Alexander von Humboldt Foundation** (German: *Alexander von Humboldt-Stiftung*) was established by the German Reich in 1925. Its main purpose was now to support foreign students and later academics and doctoral candidates during their stay in Germany. In 1945, the Foundation ceased functioning. Today's Alexander von Humboldt Foundation was established by the Federal Republic of Germany on 10 December 1953.

Mutual understanding coupled with academic freedom and excellence have remained the Foundation's creed to this day. The Alexander von Humboldt Foundation is funded by the Federal Foreign Office, the Federal Ministry of Education and Research, the Federal Ministry for Economic Cooperation and Development, the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety as well as a number of national and international partners; it promotes international academic cooperation between excellent scientists and scholars from Germany and from abroad.

Every year the Foundation grants more than 700 competitive research fellowships and awards, primarily going to academics from natural sciences (mathematics included) and the humanities. It allows scientists and scholars from all over the world to come to Germany to work on a research project they have chosen themselves together with a host and collaborative partner. In particular, these fellowships and awards include a number of large prizes, such as Humboldt Professorships and Sofia Kovalevskaya Awards. Fellowships and awards from the Foundation are considered to be among the most prestigious and generous awards in Germany; the alumni network is the foundation's greatest asset, comprising over 26,000 Humboldtians throughout the world, including 50 Nobel Prize Winners.

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THURSDAY – 10 MARCH 2016

09:30 – 10:00 **WELCOME REFRESHMENTS**

10:00 – 10:15 **OPENING REMARKS**

10:15 – 10:30 **Testimonial** – *The Sponsorship Portfolio of the Alexander von Humboldt Foundation*

10:30 – 11:30 **Seth Stein, *Northwestern University, U.S.A***
Playing Against Nature:
Integrating Science and Economics to Mitigate Natural Hazards in An Uncertain World

11:30 – 12:15 **Aral Okay, *Istanbul Technical University, Turkey***
Tectonics of the Eastern Mediterranean and Black Sea Region

12:15 – 13:00 **Jean-Paul Montagner, Institut de Physique du Globe de Paris, France**
Anisotropic Seismology

13:00 – 14:00 **LUNCH BREAK**

14:00 – 14:45 **Thorsten Becker, *University of Southern California, U.S.A***
Seismic Anisotropy Constraints on Mantle and Lithospheric Dynamics

14:45 – 15:15 **Claudio Faccenna**, ***Università Degli Studi Roma Tre, Italy***
Mantle Dynamics in the Mediterranean

15:15 – 15:45 **Andreas Fichtner**, ***Swiss Federal Institute of Technology, Zurich, Switzerland***
Imaging the Earth from Sedimentary Basins to the Deep Mantle

15:45 – 16:15 **TEA-COFFEE-REFRESHMENTS**

16:15 – 16:45 **Rainer Kind*, GeoForschungsZentrum, Potsdam, Germany***
The Structure of the Mantle Lithosphere in Central Europe from S-Receiver Functions

16:45 – 17:15 **Haydar Karaoğlu, *Institut de Physique du Globe de Paris, France***
Towards the Next Generation Global Upper-Mantle Anelastic Model

17:15 – 17:45 **Xiaohui Yuan*, GeoForschungsZentrum, Potsdam, Germany***
Lithospheric Structure of NW Namibia

17:45 – 18:15 **Jaroslava Plomerova, *Academy of Sciences of the Czech Republic, Prague***
Advances in Seismic Anisotropy Studies and Teleseismic Velocity Tomography Images of the Upper Mantle

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FRIDAY – 11 MARCH 2016

09:30 – 10:00 **WELCOME REFRESHMENTS**

10:00 – 10:45 **Greg Houseman, *University of Leeds, U.K***

The Faultlab Project: *The Localization of Deformation Across The North Anatolian Fault Based on Geodetic and Seismic Measurements*

10:45 – 11:15 **Fatih Bulut, *GeoForschungsZentrum, Potsdam, Germany***

Investigating the Earthquake Cycle Using Long Term Seismicity in NW Turkey

11:15 – 11:45 **Stathis Stiros, *University of Patras, Greece***

Finite Fault Modeling from Inversion of Geodetic Data:
Approaches, Limitations, and Uncertainties

11:45 – 12:15 **Dimitrios Papanikolau, *National and Kapodistrian University of Athens, Greece***

Active Tectonics and Seismic Hazard in the Oblique Opening Skyros Basin, Greece

12:15 – 13:30 **LUNCH BREAK**

13:30 – 14:15 **Frederik Tilmann, *GeoForschungsZentrum, Potsdam, Germany***

The 2015 Illapel Earthquake, central Chile – *A Type Case for a Characteristic Earthquake?*

14:15 – 14:45 **Andrea Morelli, *Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Bologna, Italy***

Crustal Structure and Seismic Shaking in Northern Italy

14:45 – 15:15 **Derek Schutt, *Colorado State University, U.S.A***

Moho Temperature and Mobile Lower Crust in the Western United States

15:15 – 15:45 **TEA-COFFEE-REFRESHMENTS**

15:45 – 16:15 **Russell Pysklywec, *University of Toronto, Canada***

Plate Tectonics Beyond Plate Boundaries: *The Role of Ancient Structures in Intraplate Orogenesis*

16:15 – 16:45 **Oğuz Göğüş, *Istanbul Technical University, Turkey***

The Role of Lithospheric Removal in Geodynamic Evolution of the Mediterranean

16:45 – 17:15 **Sofia-Katerina Kufner, *GeoForschungsZentrum, Potsdam, Germany***

Deep India Meets Deep Asia: *Lithospheric Indentation, Delamination and Break-Off Under Pamir and Hindu Kush (Central Asia)*

17:15 – 17:45 **Miriam Christina Reiss, *Goethe Universitaet Frankfurt, Germany***

Seismic Anisotropy in the Lithosphere/Asthenosphere System Beneath Southern Madagascar

17:45 – 18:15 **Mohammad Youssof, *University of Copenhagen, Denmark***

Seismic Imaging of Southern African Cratons

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POSTER SESSION

Judith Confal (Berlin Technical University, Germany)
Investigation of Mantle Kinematics Beneath Hellenic-Subduction Zone by Using Teleseismic Direct Shear Waves

Özcan Çakır (Çanakkale Onsekiz Mart University, Turkey)
A New Approach for Anisotropic Teleseismic Receiver Function Inversion

Yeşim Çubuk-Sabuncu (Istanbul Technical University, Turkey)
Multi-Scale Full Waveform Inversion (FWI) in the Sea of Marmara Region (NW Turkey)

Tuna Eken (Istanbul Technical University, Turkey)
Significant Seismic Anisotropy Beneath Southern Tibet Inferred from Splitting of Direct S-Waves

Murat Erduran (Çanakkale Onsekiz Mart University, Turkey)
Seismic Anisotropy Beneath Anatolian Plate from SK(K)S Splitting

Oğuz H. Göğüş (Istanbul Technical University, Turkey)
Neotectonic Evolution of Anatolia: Comparison of Geodynamical Models and Observations

Laura Gregory (University of Leeds, U.K)
Millennial Strain Partitioning and Fault Interaction Revealed by ^{36}Cl Cosmogenic Nuclide Datasets from Abruzzo, Central Italy

T. Serkan Irmak (Kocaeli University, Kocaeli, Turkey)
Seismological and Structural Features of November 9th, 2011 (M_w 5.6) Edremit-Van Earthquake

Neslihan Ocakoğlu (Istanbul Technical University, Turkey)
Morphologic and Seismic Features in the Gulfs of Gökova, Marmaris and Fethiye, SW Turkey

Gültekin Topuz (Istanbul Technical University, Turkey)
East Anatolian Plateau Underlain Largely by a Continental Crust Rather than Oceanic Accretionary Complex

Ebru Şengül-Uluocak (Çanakkale Onsekiz Mart University, Turkey)
Present-Day Dynamic Topography in Eastern Anatolia

Ergin Ulutaş (Kocaeli University, Kocaeli, Turkey)
Observations and Numerical Simulation of 28 October 2012 Earthquake, M_w *7.8*, and the Tsunami in Queen Charlotte Islands, British Columbia

Cengiz Yıldırım (Istanbul Technical University, Turkey)
Seismic History of the Cnidus Fault Zone: Inferences from Cosmogenic ^{36}Cl Surface Exposure Dating of the Fault Scarp

Seda Yolsal-Çevikbilen (Istanbul Technical University, Turkey)
Finite-Fault Slip Distribution Model and Tsunami Simulation of the 16 September 2015 Earthquake, M_w *8.3,* in Illapel (central Chile)

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SATURDAY – 12 MARCH 2016

Excursions

Scientific excursions to old City Centre of Istanbul to observe structural damages caused by earthquakes at the Topkapı Palace, the Grand Bazaar, and the Hagia Sophia Museum and surroundings provided that minimum number of researchers interested to take part.

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ABSTRACTS

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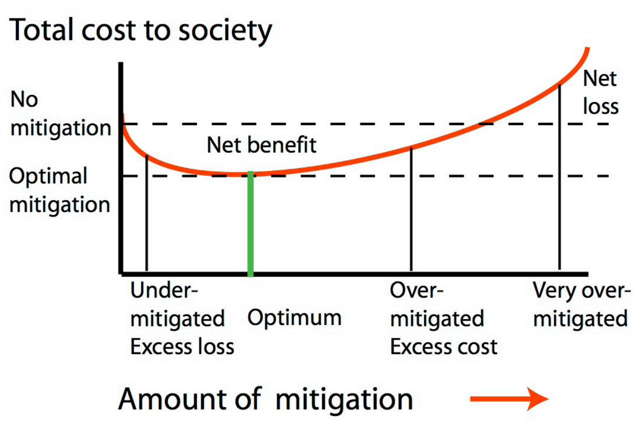
10 – 12 MARCH 2016

Playing Against Nature:
Combining Geoscience and Economics to Mitigate Natural Hazards in An Uncertain World

Seth Stein, Earth and Planetary Sciences, Northwestern University, USA (s-stein@northwestern.edu)

In trying to mitigate natural hazards, society plays a high-stakes game against nature. Often nature surprises us, when an earthquake, hurricane, or flood is bigger or has greater effects than expected from detailed natural hazard assessments. In other cases, nature outsmarts us, doing great damage despite expensive mitigation measures. Society faces the challenge of finding a level of hazard mitigation that minimizes total cost to society. That cost is the sum of mitigation costs, such as earthquake resistant construction, plus the expected loss for future earthquakes assuming a given level of mitigation. The expected loss is the sum of losses in various expected events times the assumed probability of each event. Less mitigation decreases construction costs but increases the expected loss and thus total cost. More mitigation gives less expected loss but higher total cost. Our ability to find this optimal level of mitigation that balances resources used for hazard mitigation with other societal needs (schools, hospitals, etc.), thus depends on our ability to estimate the probabilities of future events and their effects, and the uncertainties in these estimates. Although often earthquake hazard maps do a good job of describing what occurs, in other cases large earthquakes occur in unexpected places and/or produce greater-than-expected shaking. The locations, times, and magnitude of large earthquakes turn out to be highly variable. Some of the variability can be addressed by using longer time series and knowledge of plate motions, but some reflects not-yet-understood and likely chaotic behavior. As a result, some key parameters required for earthquake hazard maps are poorly known, unknown, or unknowable. Because plausible alternative parameter choices yield quite different maps, maps have significant uncertainties, and detailed hazard maps based on past earthquakes may not do better predicting future shaking than maps in which the hazard is assumed to be more uniform. This possibility is suggested by comparing how well a 510-year-long record of earthquake shaking in Japan is described by the Japanese national hazard maps, uniform maps, randomized maps, and smoothed maps. Similarly in Nepal, where GPS data show no significant variation in coupling between areas that have had recent large earthquakes and those that have not, past earthquakes may not show which parts are more at risk, and the entire area may best be regarded as equally hazardous.



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Tectonics of the Eastern Mediterranean and Black Sea Region

Aral I. Okay, Eurasia Institute of Earth Sciences, and Department of Geological Engineering, Istanbul Technical University, Turkey (okay@itu.edu.tr)

In the last 600 million years the Eastern Mediterranean and the Black Sea region were located on and around the lithospheric plate margins. This has produced a complicated but highly variable and interesting geology. On a very broad scale the history of the region can be described as the growth of Laurasia by the amalgamation of Gondwana-derived terranes. The core of Laurasia is represented by the Ukranian shield north of the Black Sea. It consists of Archean and Paleoproterozoic crystalline rocks, which have not undergone any significant contractional deformation in the last 1000 million years. In contrast the region to the south have been repeatedly deformed during the late Neoproterozoic (Pan-African), Carboniferous (Variscan), Triassic (Cimmeride) and Late Cretaceous-Recent (Alpide) events.

Gondwana-derived terranes rimming the southern margin of Laurasia are all characterized by a late Neoproterozoic, dominantly acidic magmatism, which was produced in magmatic arcs on the northern margin of Gondwana. The accretion of these Gondwana terranes to Laurasia occurred in four major periods. These collisions were preceded by arc magmatism and major magmatic arcs of Carboniferous, Triassic, Jurassic and Cretaceous ages are recognized in the Balkans, Pontides and Caucasus. The Black Sea opened as a back-arc basin during the Late Cretaceous in a phase of arc-extension.

The records of the earliest collision of Gondwana-derived terrane with Laurasia in the Early Paleozoic are buried under the younger sedimentary cover, north of the Black Sea. The next major collision occurred during the Late Carboniferous leading to the Variscan deformation in the Balkans, Pontides and the Caucasus. The third phase during the earliest Tertiary is represented by the collision of the Anatolide-Tauride Block followed by the final Miocene collision of the Arabian Platform, which for the first time in 600 million years closed the oceanic seaway between Laurasia and Gondwana in the region. This last collision event also shaped the present day morphology leading to the uplift of Anatolia and the Caucasus. The Early Miocene subduction between the Arabian plate and Laurasia is still continuing in the Eastern Mediterranean in the Hellenic subduction zone. This remnant subduction, rather than Arabia collision gives rise to the westward translation of the Anatolian plate along the North Anatolian Fault and to the major crustal extension in the Aegean region.

notes

Anisotropic Seismology

Jean-Paul Montagner, Laboratoire de Sismologie, Institut de Physique du Globe de Paris, Université Paris-Diderot, I.U.F. Paris, France (jpm@ipgp.fr)

Seismic anisotropy, in spite of its inherent complexity is becoming an important ingredient for explaining various kinds of seismic data. For example, global tomographic models have been improved over years not only by an increase in the number of data but more importantly by using more general parameterizations, now including anisotropy (radial anisotropy and then general slight anisotropy) and anelasticity.

The imaging of seismic anisotropy renews our vision of upper mantle dynamics because different physical processes (cracks or fluid inclusions, lattice preferred orientation of crystals, fine layering) related to stress field and/or strain field give rise to observable seismic anisotropy (S-wave splitting, surface wave radial and azimuthal anisotropies).

Surface waves provide an almost uniform lateral and azimuthal coverages, particularly below oceanic areas and are used to image large scale (>1000km) lateral heterogeneities of velocity and anisotropy in the upper mantle (0-660km depth). The interpretation of anisotropy makes it possible to relate surface geology and plate tectonics to underlying mantle convection processes, and to map at depth the origin of geological objects such as continents, mountain ranges, slabs, ridges and plumes. Usually, several different processes create a complex stratification of anisotropy which can be unraveled by simultaneously taking account of effects of anisotropy on body waves and surface waves. We will show how to determine the LAB (lithosphere-asthenosphere boundary) topography from surface waves and how the radial and azimuthal anisotropies provide strong constraints on the nature of a tectonic plate.

Another promising application regards the temporal variations of anisotropy before and after an earthquake. Some evidence of such changes will be presented for the Parkfield 2004 earthquake, and for the Iwate-Miyagi 2008 earthquake from continuous seismic noise.

In conclusion, anisotropic seismology covers a wide range of applications for structural geologists and geodynamicists for understanding the dynamics of the crust and the mantle. Its interpretation makes it possible to relate surface geology, crustal deformation and plate tectonics to underlying mantle convection processes.

notes

Seismic Anisotropy Constraints on Mantle and Lithospheric Dynamics

Thorsten W. Becker, University of Southern California, Los Angeles CA, USA (twb@usc.edu)

Seismic anisotropy records a range of components of Earth's thermo-chemical evolution and so provides key insights into mantle convection across a range of spatio-temporal scales. Here, I review recent results from the analysis of upper mantle anisotropy. On global scales, the oceanic lithosphere–asthenosphere system appears to record plate formation at spreading centers at shallow depths, likely including the effects of incorporation of melt layering. At larger depths, the active formation of shear fabrics due to asthenospheric flow appears to lead to lattice preferred orientation (LPO) of intrinsically anisotropic crystals, much of which can be captured by flow models including mineral physics approaches. Anisotropy patterns with depth can be used to define a mechanical lithosphere which appears consistent with a thermal definition, with no indication of decoupling due to thin, lubricating channels as suggested recently. However, the mechanical lithosphere encompasses different petrological layers and associated seismic discontinuities. The mantle flow component of seismic anisotropy in the asthenosphere can be explained by shear as approximated by absolute plate motions, to first order, and almost statistically optimally so if the plate-motion reference-frame is chosen as spreading-orientation aligned. This reference frame is consistent with geodynamic estimates of net rotation of the surface with respect to the deep mantle expected for a strong, old continent – weak oceanic asthenosphere viscosity contrast. Moreover, it matches global hotspot motion estimates, provides a clear description of subduction zone trench motions, may be appropriate for the last ~30 Ma, and so guide plate reconstruction efforts. When LPO is estimated from actual mantle flow computations based on density models derived from seismic tomography instead, a convincing and alternative description of background anisotropy arises for most regions underneath oceanic plates. Exceptions of poor model performance are found underneath ridges, where reworking of LPO may not be captured well by existing descriptions, and in regions with intraplate deformation. This hints at a way to complement geodetic and seismic strain measurements for plate stability and "coupling" with the underlying mantle.

Based on the success of such global background models, recent anisotropy modeling on the smaller scales of the Mediterranean mobile belt has helped in understanding how subduction is interacting with continental lithosphere, and how slab morphology changes (e.g. rollback, fragmentation) and plume influx (perhaps in the western Mediterranean, likely underneath the Afar-Arabia-Anatolia-Aegean system) are expressed in seismic anisotropy. I review our efforts in delineating slab sinkers underneath the Alboran, and lithospheric channeling and plume and volcanism advance underneath Arabia. Such models can explain many of the patterns of azimuthal anisotropy in the Mediterranean, including across the North Anatolian fault zone, but fail to explain other features which are within numerical resolution. This points to a number of future avenues for model refinement, substantiating our insights into asthenosphere-lithosphere interactions past and present, and guiding future structural seismology experiments to test key geodynamic hypotheses.

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10 – 12 MARCH 2016

Mantle Dynamics in the Mediterranean

Claudio Faccenna[1] and Thorsten W. Becker[2]

[1] Dip. Scienze, Università Roma TRE, Rome, Italy (claudio.faccenna@uniroma3.it)

[2] University of Southern California, Los Angeles CA, USA (twb@usc.edu)

The Mediterranean offers a unique avenue to study the driving forces of tectonic deformation within a complex mobile belt. Lithospheric dynamics are affected by slab rollback and collision of two large, slowly moving plates, forcing fragments of continental and oceanic lithosphere to interact. Here, we review the rich and growing set of constraints from geological reconstructions, geodetic data, and crustal and upper mantle heterogeneity imaged by structural seismology. We discuss a conceptual and quantitative framework for the causes of surface deformations. Exploring existing and newly developed tectonic and numerical geodynamic models, we illustrate the role of mantle convection on surface geology. A coherent picture emerges which can be outlined by two, almost symmetric, upper mantle convection cells. The down-wellings are found in the centre of the Mediterranean, and are associated with the descent of the Tyrrhenian and the Hellenic slabs. During plate convergence, these slabs migrated, driving return flow of the asthenosphere from the backarc regions. These currents can be found at large distance from the subduction zones, and are at present expressed in two upwellings beneath Anatolia and eastern Iberia. This convection system provides an explanation for the general pattern of seismic anisotropy in the Mediterranean, the first-order Anatolia and Adria microplate kinematics, and the positive dynamic topography of Anatolia and Eastern Iberia. More generally, it is an illustration of upper mantle, small-scale convection leading to intraplate deformation and complex plate boundary reconfiguration at the westernmost terminus of the Tethyan collision.

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Imaging the Earth from Sedimentary Basins to the Deep Mantle

Andreas Fichtner, Swiss Federal Institute of Technology (ETH), Zurich, Switzerland
(andreas.fichtner@erdw.ethz.ch)

Complex interactions of small- and large-scale processes are characteristic for the physics of the Earth, and their proper quantification is key to the integration of interdependent geophysical systems that are today mostly treated as isolated.

Inferring Earth structure over a wide range of scales is the long-standing goal of seismic tomography. While much progress has been made in recent years, the following challenges still seriously limit tomographic resolution: (1) the limited data coverage that results from the irregular distribution of sources and receivers, (2) the consistent integration of small- and large-scale features into one tomographic model, and (3) our inability to assess uncertainties quantitatively and efficiently.

To address these challenges, we developed a multi-scale full waveform inversion that assimilates complete teleseismic and regional seismograms in a broad frequency band from 1/200 to 1/5 Hz. Being based on spectral-element modelling and adjoint techniques, our method simultaneously solves multiple regional- and continental-scale inverse problems in order to jointly resolve Earth structure with resolution lengths ranging from around 10 to more than 5000 km. Different scales are coupled via non-periodic homogenisation, and tomographic resolution is quantified using a random probing technique of the Hessian.

We apply our method to Europe and Western Asia, where resolution is particularly high beneath the North Atlantic, the western Mediterranean and Anatolia. The multitude of geologically interpretable features extends from the shallow surface into the deep mantle. They include the Iceland-Jan Mayen plume system, the lithospheric expression of the North Anatolian Fault Zone, the morphology of subducting lithospheric slabs beneath the western Mediterranean region, as well as the Rhone, Po, Molasse and Ebro basins.

The extension of our approach to the globe is the backbone of an emerging Collaborative Seismic Earth Model (CSEM) that assimilates the complete range of seismic data into one consistent model of the Earth's interior with the help of community contributions. Harnessing the collaborative potential of the seismic community, the CSEM is intended to go beyond the Earth models that individual researchers can construct today and to bridge the gap between crust and mantle tomography on a global scale.

notes

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10 – 12 MARCH 2016

The Structure of the Mantle Lithosphere in Central Europe from S-Receiver Functions

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Data from about 650 permanent and temporary seismic broadband stations accessed from the open EIDA Archive yielded about 49.000 S-receiver functions. Selection criteria were a signal-to-noise ratio of at least two of the S signal on the SV component, low noise on the P component before the S arrival time and a relatively good approximation of the delta impulse on the SV component after deconvolution. All traces were checked visually. The time domain traces were migrated to depth domain by back projection along the ray path. Smooth images of major discontinuities in the upper mantle were obtained by applying an eight-seconds low-pass filter. Observations of the Moho and the discontinuity at 410 km depth serve as a check of the quality of the analysis.

We observe two widespread negative (i.e., downward reduction in velocity) discontinuities. The shallower one in about the 50 km to 150 km depth interval occurs everywhere in the study area and is interpreted as the lithosphere-asthenosphere boundary (LAB) in Phanerozoic Europe. According to similar observations in the north American craton, it is interpreted as mid-lithospheric discontinuity (MLD) in the east European craton (EEC). The second negative discontinuity seen beneath the EEC, the Trans-European Suture Zone, the Bohemian Massive, and parts of the Pannonian Basin lies at a depth interval of about 150 km to 300 km. It is interpreted as cratonic LAB reaching well the S and E of the Tornquist-Teisseyre Zone, which is considered the boundary of the EEC at the shallower levels. The deeper cratonic LAB has anomalous topography: Below the Pannonian Basin it shallows to c. 150 km but deepens to c. 300 km below the Bohemian Massif. There is a jump in the cratonic LAB along the northern edge of the Bohemian Massif, where the LAB suddenly changes depth from 200 km in the north to 300 km in the south. We tentatively interpret these observations as a result of overthrusting the EEC mantle lithosphere during the Variscan orogeny, which also lead to partly delimitation of the EEC mantle lithosphere deep underneath the Bohemian Massif.

The subduction below the Alps seems to be confined to about 150-200 km depth, consistent with the previously published results of P-wave tomography. We confirm the southeast subduction direction below the central Alps,but the data below the eastern Alps are less clear concerning subduction direction. We see also indications of northeastward subduction below the Dinarides to about 200 km depth in an area where previous P-wave tomography indicates a slab gap.

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Towards the Next Generation Global Upper-Mantle Anelastic Model

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Determining the 3D intrinsic seismic attenuation structure of the Earth is important for addressing the origin of observed heterogeneities. Being more sensitive to thermal structure, attenuation parameters can provide additional constrains on this issue by distinguishing the heterogeneities caused by thermal variations from the compositional ones. Such an endeavor also has the potential to complement the information provided by elastic tomography by taking the physical dispersion into consideration.

The major challenge in mapping the attenuation parameters is the separation of anelastic effects, which manifest themselves through dispersion and amplitude decay, from the elastic ones such as (de)focusing and scattering. To address this issue, we begin our inversion with a good prediction of the elastic gradients as preknowledge, namely the SEMUCB-WM1 model [French and Romanowicz, 2014]. As the methodology, we follow a hybrid approach, using the spectral element method for the forward modeling [Capdeville et al., 2003] and normal-mode based theory (NACT - Li and Romanowicz [1995]) for the kernel computation. The coupled Spectral Element Method allows a complete description of the 3D wavefield, and is computationally economical when applied to a restricted region of the earth (i.e. the upper mantle) and relatively low frequencies (here down to 60 s). NACT based kernel computation, on the other hand, takes into account both the effect of horizontally averaged structure along the great circle between the source and receiver and any further correction due to cross-branch modal coupling. This approach has proven to be successful in developing high resolution global tomographic models [French and Romanowicz, 2014].

We have previously developed a 3D upper-mantle shear attenuation model based on time domain waveform inversion of long period (T > 60s) fundamental and overtone surface wave data [Gung and Romanowicz, 2004]. However, at that time, resolution was limited to very long wavelength structure, because elastic models were still rather smooth, and the effects of focusing could only be estimated approximately, using asymptotic normal mode perturbation theory. We have extended our methodology further to develop the next generation global upper-mantle attenuation (Q_μ) model. As our inversion strategy, we follow a joint inversion scheme that addresses both the elastic and anelastic parameters. Additionally, we invert for frequency independent source and receiver amplification terms to recover major source and receiver site effects. Here, we present the results of synthetic tests that confirm our inversion strategy, as well as the preliminary results towards the construction of the upper-mantle anelastic model.

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10 – 12 MARCH 2016

Lithospheric Structure of NW Namibia

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Northwestern Namibia at the landfall of the Walvis Ridge was affected by the Tristan da Cunha mantle plume during continental rupture between Africa and South America. We use data from an amphibian passive-source seismological network to investigate the mantle plume-lithosphere interaction. An over thickened crust with high Vp/Vs ratio was observed at the landfall of the Walvis Ridge, implying magmatic underplating. Receiver functions also reveal an interface with negative velocity contrast in the mantle at an average depth of 80 km that we interpret as the relics of the lithosphere-asthenosphere boundary (LAB). This interface is shallower than one would expect from other geophysical and geothermal data for the present-day LAB in this area and might therefore indicate the depth of thermal erosion of the lithospherie. The mantle transition zone discontinuities at 410 and 660 km are clearly observed by P wave receiver functions. In much of the study area the P-to-S converted phases of both discontinuities arrive 1.5s earlier than in the plume-unaffected continental interior further east. The early arrival of the two discontinuity phases with constant separation would suggest a high velocity in the upper mantle or a thick lithosphere beneath the study area, which may imply that the lithosphere has regained a large thickness during the last 132 Myr. However, the present-day LAB is weak or poorly visible in the receiver functions with converted waves, which might indicate a gradual impedance contrast. Surface wave tomography reveals a thick lithosphere with a thickness of more than 175 km over a large area extending farther south of the Congo craton. Thermal cooling of continental lithosphere cannot produce the amount of lithospheric thickness required here. Hence depleted material in the remnant mantle lithosphere is likely the primary cause for the high velocities required in the area where the plume played a key role in the development of the Parana-Etendeka basalts.

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10 – 12 MARCH 2016

Advances in Seismic Anisotropy Studies and Teleseismic Velocity Tomography Images of the Upper Mantle

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Considering only isotropic wave propagation and neglecting anisotropy in teleseismic body-wave tomography is a simplification obviously incongruous with current understanding of the mantle-lithosphere plate dynamics. Furthermore, in solely isotropic high-resolution tomography results, potentially significant artefacts (i.e., amplitude and/or geometry distortions of 3D velocity heterogeneities) may result from such simplification. Moreover, a necessity to abandon an approximation of the upper mantle structure solely by the azimuthal anisotropy and to switch to fully 3D anisotropic models with generally inclined symmetry axes emerged from detail analyses of body-wave anisotropic parameters.

Therefore, we have developed a code for anisotropic teleseismic tomography (AniTomo), which allows us to invert the relative P-wave travel time residuals simultaneously for coupled isotropic-anisotropic P-wave velocity models of the upper mantle. Apart from isotropic velocity heterogeneities, a weak hexagonal anisotropy is assumed to be responsible for the observed P-wave travel-time residuals. As no limitations on orientation of the symmetry axis are prescribed in the code, we allow a search for anisotropy oriented generally in 3D. This represents a unique approach among recent trials that otherwise incorporate only azimuthal or radial anisotopy separately into body-wave tomography. The presented code for retrieving anisotropy in 3D thus enables its direct applications to datasets from tectonically diverse regions.

notes

The Faultlab Project:
The Localization of Deformation Across The North Anatolian Fault
Based on Geodetic and Seismic Measurements

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The FaultLab Project is a multi-disciplinary (geodesy, seismology, structural mapping and mechanical modelling) study of the North Anatolian Fault zone in Turkey with major funding from the UK Natural Environment Research Council. The North Anatolian fault marks the northern boundary of a broad zone of diffuse deformation that extends right across the Anatolian region and out into the Aegean Sea. The North Anatolian Fault is well known as the locus of numerous damaging earthquakes, most recently the disastrous 1999 events centred on Izmit and Duzce. The DANA array was a temporary broadband seismic array installed across the North Anatolian Fault zone east of Izmit during 2012-2013, as a collaborative effort of the University of Leeds, Kandilli Earthquake Observatory and Research Institute and Sakarya University. The array, with a typical station spacing of 7 km, crosses the Fault zone around Lake Sapanca, where the fault zone is bifurcated into two major fault strands. Receiver Function images from the DANA array show a crustal stratification which distinctly changes on a length scale of a few km as the fault strands are crossed from Istanbul zone on the north side, across the Armutlu-Almacik zone, to the Sakarya zone on the south side. From these images we infer that shear zones (if not sharp faults) extend beneath the surface traces of both fault strands, at least to the depth of the Moho and possibly into the upper mantle. In the same region geodetic data that precede and follow the 1999 events describe the inter-seismic and post-seismic deformation rates. Based on models of the seismic cycle with a visco-elastic crustal layer, these data led us to infer a localized zone of low viscosity material in the mid-crust beneath the Northern fault strand (on which the major displacement occurred in the 1999 earthquakes). The low viscosities are required to enable the rapid release of elastic stress in the post-seismic period but this low-viscosity zone must be embedded in a layer for which the effective viscosity is much (~2 orders of magnitude) greater, in order that these elastic strains are not simply dissipated by viscous creep as they develop during the inter-seismic period. The low viscosity zone also is inferred to extend roughly equal distances (~10-20 km) either side of the active fault (the Northern strand). However, the physical cause of the low viscosity zone is not readily apparent when compared with the seismic images, or with earlier resistivity surveys which found low resistivities only in the Armutlu-Almacik zone between the two fault strands. The explanation of the low viscosity zone remains a matter of investigation.

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10 – 12 MARCH 2016

Investigating the Earthquake Cycle Using Long Term Seismicity in NW Turkey

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Large earthquakes are the occasional failure of plate-boundary and intra-plate fault zones accommodating permanent tectonic deformation and elastic-rebound strains. Failure occurs when accumulated tectonic deformation exceeds the frictional strength of the Earth's crust. Earthquake generation process develops as separate stages of a cycle, which is controlled by the frictional strength of the faults and surrounding strain fields. Studying different stages of the earthquake cycle requires studying seismicity and structure of the Earth's crust along recent and potential future rupture zones. In practice, this needs to be addressed on a seismically highly active region that is monitored with dense seismic networks. Under these aspects, Turkey is ideally suited to be the primary test ground. In this study, seismicity of NW Turkey has been investigated in detail in order to elaborate on those complex processes. Microseismic activity is analyzed to investigate variation in brittle deformation at different physical stages of the earthquake cycle for the two major earthquakes (the 1999 M 7.4 İzmit and the 2014 M 6.9 Aegean earthquakes).

Seismicity catalog consisting of ~20.000 earthquakes has been investigated to determine statistically reliable range. Seismicity rates are analyzed within this range to locate high/low strain fault sections in space and to differentiate between physical stages of the earthquake cycle in time. Furthermore, well-located pre-shocks and foreshocks are used to characterize physical process taking place until the earthquake failure. The two major earthquakes have been preceded by almost a decade-long period of enhanced micro-earthquake activity representing a brittle process preparing the failure. This preparation stage is characterized also in space by lateral migration of micro-earthquakes moving systematically towards the mainshock hypocenter within a time period of roughly a decade. The Sea of Marmara segments of the North Anatolian Fault show a rather temporally uniform seismicity trend for the time period of analysis suggesting that those segments are not yet in preparation stage of a large earthquake.

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Finite Fault Modeling from Inversion of Geodetic Data: Approaches, Limitations, and Uncertainties

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Assuming elastic half-space, surface deformation (usually slip vectors) is connected with the seismic faults with algebraic formulas. Hence, the parameters defining a finite seismic fault can be determined simply solving a system of observations equations. However, no formal solution of such system of equations (inversion) is possible because of the large number n of unknowns (an idealized rectangular fault of uniform slip is defined by n=9 variables); observation equations are highly non-linear; the number of observations and of unknown variables are usually not equal; observations are contaminated by errors; no reliable approximate estimates of the unknown parameters are usually possible.

To overcome this problem, different approaches have been proposed: (1) trial-and-error techniques with forward computations, (2) least-squares techniques assuming approximate solutions; (3) inversion for some of the fault parameters a priori assuming fixed all others; (4) gradual optimization of two variables at a time, assuming the other variables constant until all variables are optimized; (5) searches using Monte Carlo or deterministic approaches in defined search spaces. All these approaches are based on the criterion of mean minimum misfit, which cannot guarantee unique or "global" solutions and focuses on a single solution, the quality of which is occasionally derived from statistics of randomly selected points around the selected solution. Mean misfit is sometimes improved assuming additional faults that, however, lead to algebraically underdetermined problems and statistically uncontrolled solutions.

An alternative inversion method, the TOPological INVersion was recently proposed. This method is based on the repeated "scanning" (exhaustive search) of all potential solutions (search space) in a discretized R^n (hyper)space using forward calculations only. Each observation equation is transformed into an absolute-value inequality in terms of the standard error of the measurement and of a single optimization parameter k. For selected values of k all the (hyper) grid points of the selected R^n search space are scanned, and is tested whether some of them satisfy all observation inequalities (Boolean approach). Optimization is based on the value of k leading to the minimum number of grid points defining compact clusters; the optimal cluster contains the "true" solution(s). Best solutions and their covariance matrices can be determined using first and second statistical moments. Mean misfits can also be computed independently.

The proposed algorithm has been tested using synthetic data and has been used in the finite fault modeling of several earthquakes assuming a single or a double fault.

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Active Tectonics and Seismic Hazard in the Oblique Opening Skyros Basin (North Aegean Sea), Greece

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Oceanographic research including swath bathymetry and single channel air-gun lithoseismic profiles was carried out in Skyros Basin, North Aegean Sea. Morphotectonic analysis and the interpretation of the lithoseismic profiles have resulted in the compilation of the tectonic map of the Skyros Basin. The map shows all the faults, both the major marginal faults as well as the secondary faults that accomnodate deformation within the internal part of the basin. Important throws of several hundred meters up to more than 1km are extracted as well as considerable strike-slip components since Middle Pleistocene time.

The overall geometry of the basin is shaped by a major slope discontinuity, separating the continental platform from the continental slope at depths between 200-400m. The basin forms an equilateral triangle. Its base is 50km long NW-SE trending at the southwest, parallel to the Skyros Island coastline, whereas its pic is located at the northeast, north of Lesvos Island. The basin comprises 9 sub-basins at varying depths ranging from 1200m at the southwest to 600m to the northeast and is structurally divided into three parts: i) the eastern part forms a longitudinal semi-graben with one sub-basin 45km long trending ENE-WSW, but only 5-8 Km wide at depths varing between 600-700m. This sub-basin is bounded to the south by a marginal fault of >1.5km throw but with unknown horizontal displacement. ii) the central part that forms the predominant part of the triangle with 45 Km long NW-SE trending base and 70km long axis at the NE-SW direction. The central part corresponds to an assymetric graben with a 70km long major marginal fault with >1500m throw along its southern slopes and a 70 km long antithetic fault with >400m throw along its northern slopes. It comprises 5 sub-basins with depths ranging between 950-700m, bounded by important E-W trending strike slip fault zones, characterized by flower structures, with minor vertical components ranging from a few meters up to 200m. iii) the western part of the basin trends NW-SE, is 55 Km long and 25 Km wide, revealing a NW-SE tectonic graben. It comprises two sub-basins, oriented NW-SE separated by an intermediate transverse fault zone. The throw of the western marginal faults offshore Skyros Island exceeds 1200m, whereas the throw of the parallel faults creating the NW-SE tectonic graben is limited to a few hundred meters. It should be emphasized that the Alpine basement was not detected in the lithoseismic profiles of the western and central parts of the basin, where the postAlpine sedimentary sequences exceed 700m of thickness, contrary to the eastern part, where the maximum thickness was determined at 600m. The length of the faults range between a few tens of km up to 111 km, indicating that these seismic sources have the potential to generate strong earthquakes up to 7.5 magnitude. The vast majority of the mapped seismic sources have not been ruptured or recorded in the historical data, implying that the seismic hazard of the area might be underestimated.

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The 2015 Illapel Earthquake, central Chile: A Type Case for a Characteristic Earthquake?

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in collaboration with **Y. Zhang, M. Moreno, J. Saul, F. Eckelmann, M. Palo, Z. Deng, A. Babeyko, K. Chen, J. C. Baez, B. Schurr, R. Rang, and T. Dahm**

On September 16, 2015, the convergent Chilean margin again experienced a great subduction megathrust earthquake. The MW=8.2 Illapel earthquake occurred in the Metropolitan segment north of where the Juan-Fernandez ridge meets the Chile trench and subduction style and geometry change over a short distance. Combining GPS displacement measurements, InSAR interferograms, strong motion data, broadband seismological waveforms and backprojection of high frequency teleseismic signals we derive a comprehensive description of the coseismic rupture. Further, we determine accurate depths for the mostly offshore aftershock sequence by careful observations of teleseismic depth phases and derive moment tensors for the larger earthquakes from waveform modelling of body- and surface waves. The rupture nucleated near the coast but then propagated to the north and updip. The resulting simple rupture geometry is approximately circular with a peak slip of ~6 m, and a diameter of approximately 100 km, centered below the middle slope of the forearc. Forward modelling of tsunami propagation for this model successfully predicts approximate tsunami wave heights measured at 3 tide gauges along the North Central Chile coast, confirming that the rupture diminished towards the trench. Similar to previous observations, high frequency seismic radiation is mostly emitted downdip of the region of most intense slip, but unlike in most previous events, the high frequency emitters do not track the whole rupture along-strike but are confined to a small region within $\ sim 50$~km of the epicenter. The time evolution of high frequency seismic radiation also peaks earlier than the long period rupture evolution, indicating that the final phase of the rupture progressed smoothly. The aftershocks extend significantly beyond the limits of the main rupture in both north and south direction; their pattern of propagation suggests triggering by coseismic changes to the Coulomb failure stress. Plate interface events dominate the aftershock sequence but there are also some thrust events in the forearc crust and some shallow normal faulting events in the oceanic crust below the trench. In 1943, an earthquake of comparable along-strike extent occurred in the Illapel area. The similar extent of the aftershock zone and tsunami heights therefore make this part of the margin a candidate site for generating characteristic earthquakes, in particular as the 1943 event was itself preceded by an event in 1880, again with apparently the same part of the margin affected. The approximate match of peak slip and accumulated slip deficit in the 72 years since the 1943 event also support this interpretation. However, the 1943 Illapel event appears to have had a significantly shorter source time function and probably a smaller magnitude than the 2015 event, pointing to difference in the detailed rupture evolution. The coupling is mostly close to fully locked in this area at least along the coast line but nevertheless the coseismic rupture is associated with a local peak in the locking pattern, whereas a distinct narrow partially interseismically creeping area is found just to the south of the main rupture. The northern transition to lower locking is more gradual but also here the rupture can be said to have terminated against a zone of reduced locking. Although locally the recent Illaped earthquake has relieved much of the accumulated stress, the segment immediately adjacent to the north remains unbroken since 1922, and presents a serious earthquake and tsunami hazard.

notes

Crustal Structure and Seismic Shaking in Northern Italy

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Detailed knowledge of the crustal structure of the Alps and surrounding foreland basins has many potential implications for geosciences in general, and, specifically, for seismology because of its relevance for understanding earthquake occurrence and seismic shaking. I will focus specifically on northern Italy: although marked by relatively infrequent seismicity, with long inter-event times and moderate magnitude, seismic risk is significant here because of high economic exposure of the same sedimentary basins, that often generate local amplification of ground motion. I will review recent studies on this subject, based on a range of different techniques. Earthquake-based tomography bring in the more general picture: P-wave travel time seismic tomography at a regional scale effectively represent the main contrast between plain and mountain chain, and the inner structure of the mountain chain, mapping lithological differences (e.g., the so-called Ivrea high velocity body). These results compare well with the S-wave velocity structure, that may be obtained by inversion of earthquake-generated surface waves and empirical Green functions derived from correlation of ambient noise. Low-velocity areas beneath the Po Plain and Molasse basin contrast with the crystalline crust under the Alpine mountain belt. However, at present the best resolution can be derived by integrating results from active-source studies, that have been extensively performed in the sedimentary plain for hydrocarbon research. I will show that such a model is able to reproduce the main characters of seismic wave propagation, such as higher amplitudes and longer duration in soft sediment sites, through deterministic simulations of wave propagation in the 3D model. This computational setup may therefore be effectively used to simulate hypotetical earthquakes – such as those known historically – also appraising effects of finite seismic sources. Hybrid techniques – complementing deterministic calculation with stochastic computation at shorter period – allow to simulate frequencies of specific engineering interest. Although it does not seem feasible to improve knowledge about structural discontinuities in the present model using passive-source data (either from earthquakes or ambient noise), it seems instead possible to adjust P and S wave velocities and their lateral variations within a given structural unit inverting seismological data. Higher resolution ambient noise measurements are being used to improve this model, as well as information on ellipticity ratio of Rayleigh waves – that only depends on local structure directly beneath a seismographic station, with a sensitivity kernels confined to shallower depths than phase or group velocity at the same period. Strong sensitivity of Rayleigh wave ellipticity on slow, shallow, crustal structure make an excellent point for improvement of sedimentary basin models to be used to reproduce seismic ground motion amplitudes. The whole wider Alpine region is target of renewed general interest. The most recent collaborative seismological undertaking is the ongoing multi-national project AlpArray, a European initiative to integrate the existing, spread, seismographic infrastructure with a large temporary array. AlpArray will be an excellent occasion to improve high-resolution imaging of the structure of this region, and also to set up a new collaborative model in the European seismological community. This discussion may thus conclude with some evaluation of prospects and expected results from AlpArray.

** main collaborators*: Irene Molinari (ETH-Z), Julie Baron (INGV), Piero Basini (Total SA), Andrea Berbellini (INGV), Lapo Boschi (UPMC), Lucia Gualtieri (LDEO), and Piero Poli (MIT)

notes

Moho Temperature and Mobile Lower Crust in the Western United States

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We use measurements of mantle P-wave velocity from the Moho refracted phase, Pn [Buehler and Shearer, 2010, 2012] and mineral physics [Schutt and Lesher, 2006, 2010] to estimate temperature in the uppermost few km of the western U.S. mantle. Relative to other approaches to modeling the deep geotherm, or mapping surface wave velocities to temperatures, Pn requires fewer assumptions and provides a less uncertain temperature within a tightly constrained depth. Moho temperatures are lowest in the high-plains region of Wyoming and western Kansas/Nebraska, while highest temperatures are observed under recent (<10 Ma) volcanic provinces where they generally exceed 850 °C. Moho temperatures east of the Laramide deformation front are also quite hot— ~850 °C, but crustal thicknesses here are 10-20 km thicker than in the Basin and Range, so these temperatures are not surprising.

Using a range of estimates of crustal heat production values, surface heat flow measurements are extrapolated to depth under the assumption of steady-state conduction, and with the constraint that Pn velocity observations are fit. Preliminary results are very encouraging, and also provide an indication of where Pn velocities are modulated by composition rather than temperature or where the assumption of steady-state heat flow is invalid. These geotherms are used to predict lithospheric bending strength parameterized as effective elastic thickness, *Te*, for various assumed rheologies. The model predictions are compared to measurements [Lowry & Pérez-Gussinyé, 2011], to show that a weak, hydrous rheology is required to fit observations in the westernmost U.S.The hydrous rheology zone significantly overlaps with the part of North America formed from accreted terranes over the last 300 M.y. To the east of this region, a dryer and stronger rheology is needed to fit the Te observations.

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Plate Tectonics Beyond Plate Boundaries:
The Role of Ancient Structures in Intraplate Orogenesis

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Although the conventional theory of plate tectonics can explain non-rigid behaviour at plate boundaries, it cannot adequately explain the processes involved in deformation and seismicity within plate interiors. Here, we consider that the pre-existing deformation or "scarring" within the mantle lithosphere may have a very long-lived presence that could incorporate deformation of the plate interior and plate boundary. Mantle lithosphere scars from continent-continent collisions could generate virtual plate boundaries that remain over long timescales, producing "perennial" plate tectonics. Local geophysical studies can map the crustal environment well, and global whole mantle tomography models are rapidly improving; yet high-resolution images of the mantle lithosphere are often not available in regions where scarring may be present. Where mantle lithosphere heterogeneities have been observed (usually interpreted simply as subduction scars), the same attention has not been afforded to them as, for example, re-activation of faults within the Earth's crust. In idealized numerical simulations, we compare how relic scarring at varying depths in the lithosphere affects patterns of deformation. High-resolution thermal-mechanical numerical experiments explore continental lithospheric deformation featuring a weakened crust and mantle lithosphere scars. Our models show that deep lithospheric scars can control the tectonic evolution of a region over shallow geological features, indicating the importance of mantle lithosphere heterogeneities. The Altyn Tagh Fault (ATF) in central China is an example of an ancient continental collision zone that undergoes periodic deformation during times of regional compression. We suggest that the ATF may be a locale where a long-lasting mantle lithosphere scar can control the subsequent crustal evolution and deformation, with ancient plate boundaries having a "perennial" plate tectonic presence.

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10 – 12 MARCH 2016

The Role of Lithospheric Removal in Geodynamic Evolution of the Mediterranean

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The geodynamic evolution of retreating ocean-continent subduction systems suggests that the back-arc lithosphere thins due to the “slab pull forcing”. While the presumed downward forcing and the resulting slab retreat inherently produce localized extension in the back-arc regions, post-orogenic shortening followed by convective thinning/extension can also play a major role to facilitate the regional extension. According to the geodynamic reconstructions, the convective thinning process has been called upon to explain a number of anomalous tectonic features (e.g slow seismic velocities in the lithosphere, asthenospheric source of volcanism and the high stretching factors) in the Alboran-Balearic Sea, Pannonian basin, Tyrrhenian sea and the Aegean sea-western Anatolia regions. The focus of this work is investigating various styles of back-arc extension models with numerical modeling technique by considering changing boundary conditions, thickness of the back-arc lithosphere and the background temperature field. Model predictions suggest that the high stretching factors (β >2) in conjunction with the development of rift basins can be produced by pre-existing (convectively removed) hot and thin back-arc lithosphere. On the other hand, models initially with undeformed-uniform back-arc lithosphere predict relatively less subsidence and extension. Accordingly, the subsidence is amplified with hotter and thinner mantle lithosphere. In the light of these findings, it can be interpreted that the anomalously thinned lithosphere and the resulting rift basins may have potentially developed by combination of the; 1) flow of hot asthenospheric mantle softening the crust (after the post-orogenic thinning) and the mechanical stretching induced by the retreating slab.

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Deep India Meets Deep Asia: Lithospheric Indentation, Delamination and Break-Off Under Pamir and Hindu Kush (Central Asia)

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The plate-tectonic paradigm permits subduction of buoyant continental lithosphere only in tow of a sinking oceanic plate and the occurrence of deep (> 100 km) earthquakes exclusively in subducting oceanic lithosphere. Yet under the Pamir in Central Asia, far away from any (paleo-) ocean basins, continental lithosphere appears to subduct by itself along one of Earth's most active intermediate (100-300 km) depth earthquake zones. We show that large-scale indentation of Cratonic Asia by a promontory of the Indian plate is causing subduction of continental lithosphere under the Pamir and that the Hindu Kush earthquakes are due to detachment of a narrow plate sliver. New precise earthquake hypocentres, source mechanisms and detailed tomographic images allow us to distinguish an arcuate, stretched and partly torn slab of Asian lithosphere beneath the Pamir and a piece of Indian lithosphere beneath the deepest Hindu Kush earthquakes. This peculiar double subduction zone arises by contrasting modes of convergence under the Pamir and Hindu Kush, imposed by the different mechanical properties of the three types of lithosphere involved.

We suggest that the buoyant northwestern salient of Cratonic India bulldozes into Cratonic Asia, forcing delamination and rollback of its lithosphere. At the same time, India's thinned continental margin tears off from Cratonic India and subducts under Asia. This resulting narrow plate sliver forms a prominent high-velocity anomaly down to the mantle transition zone. Our images show that its uppermost section is thinned or already severed and that intermediate depth earthquakes cluster at the neck connecting it to the deeper slab, providing a rare glimpse at the ephemeral process of slab break-off.

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Seismic Anisotropy in the Lithosphere/Asthenosphere System Beneath Southern Madagascar

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Madagascar is considered as a key region with respect to the assembly and break-up of the supercontinent Gondwana. Following the collision between East- and West-Gondwana (~700-650 Ma), its position was central to the Pan-African orogeny. Madagascar then separated from East Africa and later from the Indian and Antarctic plates until these processes came to a halt about 69 Ma ago. Today, Madagascar consists of different tectonic units; the eastern parts (two thirds of the island) are composed mainly of Precambian rocks, whereas sedimentary deposits dominate the western part. Furthermore, several NS to NW-SE trending shear zones characterize southern Madagascar. To increase our understanding of these structures and related tectonic processes, we installed a dense temporary seismic network in southern Madagascar. It consisted of 25 broadband and 25 short-period stations, which were in operation for up to 2 years between 2012 and 2014. The broadband stations crossed the island along an east-west profile; the eastern section was supplemented by a network of short-period stations.

We present results from shear-wave splitting analyses to infer the seismic anisotropy of the lithosphere-asthenosphere system in response to deformational processes. The polarization of the fast shear wave and the delay time between the fast and slow waves provide constraints on the anisotropic fabric. For our study, we use core phases from up to 22 events recorded at the temporary stations and the permanent GEOFON station VOI. We first apply a conventional single-event splitting analysis by minimizing the transverse component. For stations that do not show a significant azimuthal dependence of the splitting parameters, we also apply a joint inversion involving all recorded waveforms from several events. Our results exhibit delay times between 0.4 and 1.5 s. In the center of the E-W profile, fast axes are mainly oriented NNW-SSE, whereas east of the Ranotsara zone, fast axes are oriented NE-SW. We apply full-waveform FD modeling to examine the effects of various anisotropic models of the crust and mantle. Shear-wave splitting analyses are applied to the calculated waveforms in order to facilitate a comparison with the observations.

Our results indicate that recently proposed mantle flow models are insufficient to explain the small-scale variations of splitting parameters observed along our profile. Our observations are best characterized by asthenospheric anisotropy, consistent with the absolute plate motion direction of ~50°, in combination with a block of fossil anisotropy located within the lithosphere exhibiting a symmetry axis of -40°. The latter may be related to the indentation of the Antananarivo block into the metasedimentary southern part of Madagascar during the Pan-African orogeny.

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Seismic Imaging of Southern African Cratons

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We present a 3D seismic model of the southern African cratonic region from teleseismic tomographic inversion of the P- and S-body wave dataset. Utilizing 3D sensitivity kernels, we invert traveltime residuals of teleseismic body waves to calculate velocity anomalies in the upper mantle down to a 700 km depth with respect to the ak135 reference model. Various resolution tests allow evaluation of the extent of smearing effects and help defining the optimum inversion parameters (i.e., damping and smoothness) for regularizing the inversion calculations.

The fast lithospheric keels of the Kaapvaal and Zimbabwe cratons reach depths of 300-350 km and 200-250 km, respectively. The paleo-orogenic Limpopo Belt is represented by negative velocity perturbations down to a depth of ~250 km, implying the presence of chemically fertile material with anomalously low wave speeds. The Bushveld Complex has low velocity down to ~150 km, which is attributed to the chemical modification of the cratonic mantle. In the present model, the finite-frequency sensitivity kernels allow to resolve relatively small-scale anomalies, such as the Colesberg Magnetic Lineament in the suture zone between the eastern and western blocks of the Kaapvaal Craton, and a small northern block of the Kaapvaal Craton, located between the Limpopo Belt and the Bushveld Complex.

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POSTER

Investigation of Mantle Kinematics Beneath Hellenic-Subduction Zone by Using Teleseismic Direct Shear Waves

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Direct shear-wave splitting measurements based on the Reference Station Technique in the southern Aegean Sea revealed significant seismic anisotropy. The technique overcomes possible contamination from source–side anisotropy on direct S-wave signals recorded at a station pair by maximizing the correlation between the seismic traces at reference and target stations after correcting the reference stations for known receiver-side anisotropy and the target stations for arbitrary splitting parameters probed via a grid search. We initially determined receiver-side anisotropy derived from SKS splitting measurements performed at four broadband stations. Following the bootstrap approach, in which only these four stations with well-constrained SKS splitting parameters are used as seeds to determine the splitting parameters of seismic stations of the EGELADOS temporary network in an iterative manner, we obtained splitting parameters at 35 stations with good-quality S-wave signals extracted from 82 teleseismic events. The fast polarization directions (ϕ) show a general trend of NNE-SSW orientation that ranges from 5.8° to 51.8°. Two stations in the west close to the Hellenic Trench and one in the east show N-S oriented fast polarizations. In the back-arc region three stations exhibit NE-SW orientation. Split time delays (δt) vary between 1.0s and 1.6s. Employing direct S-waves enabled more stable and reliable splitting measurements, with an average of 46 individual measurements. The overall fast polarization variations tend to be similar to those obtained from previous SKS splitting studies in the region but indicate a more consistent pattern. Splitting analyses on direct shear waves resulted in larger split time delays compared to previous studies, possibly because they travel along a longer path in the same anisotropic structure. Observed differences between direct shear waves-derived (this study) and previous SKS splitting measurements could be due to the fact that S-waves propagate by sampling a broader zone in the upper mantle as well as anisotropy measurements based on insufficient number of individual SKS splitting measurements reported in earlier studies. Very consistent NNE-SSW directed anisotropic directions imply a dominant asthenospheric source due to the mantle flow exerted by the retreat of the African lithosphere along the Hellenic Trench.

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10 – 12 MARCH 2016

POSTER

A New Approach for Anisotropic Teleseismic Receiver Function Inversion

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Teleseismic receiver function inversion inherently has a problem called multiple solutions. This problem arises from too narrow slowness window from which receiver functions originate. And therefore receiver functions are not sensitive to absolute velocities of the propagating medium. In order to solve this problem surface wave information, which are sensitive to the average velocities of the medium, is added to the inversion process. This method, which is called joint inversion of receiver functions and surface waves, is frequently successfully used in geophysics. Another method to solve this multiple solution problem could be to observationally widen the receiver function slowness window utilized in the inversion process. This approach could be quite useful when the surface wave information is not readily available. In this study we suggest a new technique based on widening the slowness window and we test the proposed technique using theoretical and observed seismic data. When anisotropic seismic velocities are sought in the inversion, then the number of inverted parameters increases at least seven fold, which makes the multiple solutions problem even worse. Therefore the proposed technique should be even more effective in anisotropic structure inversion. In addition, since the surface wave information is not employed, there is expected decrease in the use of CPU time in the inversion. This research is supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK- Grant number 109Y345).

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POSTER

Multi-Scale Full Waveform Inversion (FWI) in the Sea of Marmara Region, NW Turkey

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Seismic imaging of the crust and upper mantle structure beneath NW Turkey is significant in order to get a better understanding of the regional seismotectonics. We present a 3D radially anisotropic velocity model of the Sea of Marmara and surroundings based on the full waveform inversion method. We have selected and simulated complete waveforms of 62 earthquakes ($M_w > 4.0$) occurred during 2007-2015, and recorded at ($\Delta < 10°$) distances. Three component earthquake data is obtained from broadband seismic stations of Kandilli Observatory and Earthquake Research Center (KOERI, Turkey), Hellenic Unified Seismic Network (HUSN, Greece) and Earthquake Research Center of Turkey (AFAD-DAD). The spectral-element solver of the wave equation, SES3D algorithm, is used to simulate seismic wave propagation in 3D spherical coordinates (Fichtner, 2009). The Large Scale Seismic Inversion Framework (LASIF) workflow tool is also used to perform full seismic waveform inversion (Krischer et al., 2015). The initial 3D Earth model is implemented from the multi-scale seismic tomography study of Fichtner et al. (2013). Discrepancies between the observed and simulated synthetic waveforms are determined using the time-frequency misfits that allow a separation between phase and amplitude information (Fichtner et al., 2008). The conjugate gradient optimization method is used to iteratively update the initial Earth model when minimizing the misfit. The inversion is terminated after 19 iterations since no further advances are observed in updated models. Our analysis revealed shear wave velocity variations of the shallow and deeper crustal structure beneath western Turkey down to depths of ~35-40 km. Low shear wave velocity anomalies are observed in the upper and mid crustal depths beneath major fault zones located in the study region. Low velocity zones also tend to mark the outline of young volcanic areas. The effects of anisotropy in the close vicinity of major fault zones are observed in the upper crust (down to ~10 km). Our final 3D Earth model is tested using forward wave simulations of earthquakes ($M \geq 3.7$) that were not used during the inversion process. The comparison of observed and synthetic seismograms, calculated by initial and final models, showed significant improvements in waveform fits at 8-100 sec periods.

This study is supported by The Scientific and Technological Research Council of Turkey (TÜBİTAK Project No: ÇAYDAG-114Y066), and EU–HORIZON-2020: COST Actions: Earth System Science and Environmental Management: ES1401–Time Dependent Seismology (TIDES).

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10 – 12 MARCH 2016

POSTER

Significant Seismic Anisotropy Beneath Southern Tibet Inferred from Splitting of Direct S-Waves

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We estimated a total of 12008 shear-wave splitting measurements using the reference-station technique applied to direct S-waves from 106 earthquakes recorded at 143 seismic stations of the Hi-CLIMB seismic network. Our results detect significant anisotropy in regions of southern Tibet where null or negligible anisotropy has been hitherto interpreted depending on SK(K)S measurements.

Station averaged S-derived fast polarization directions exhibit a consistent lateral variation whereas splitting time delays (TDs) indicate deviations particularly at stations located south of the Indus–Tsangpo Suture Zone. The fast polarization directions (FPDs) tend to rotate from (a) the NE–SW to E–W to the south of the Indus–Tsangpo Suture Zone (b) NE–SW to ENE–SSW between Bangong–Nujiang Suture Zone and the Indus–Tsangpo Suture Zone (ITSZ). They are oriented along the E–W direction to the extreme north of the profile.

Observed splitting time delays (δt) vary between 0.45 and 1.3 s south of the ITSZ (< 30°N latitude), while they range from 0.9 to 1.4 s north of it. The overall trends are similar to SKS/SKKS results. The discrepancies, however, may be the indication of non-vertical propagation path effect of direct S waves sampling the upper mantle within a more expanded area differently with respect to SKS waves. Second option for those differences in S- and SKS-derived splitting delay times can be due to the insufficient number of SKS observations. We observe a significant anisotropic strength from splitting measurements with ~0.8 s of delay times beneath Himalaya and interpret it as the influence of a complex deformation pattern in the region that can be best explained by the combined effects of deformation related to shear at the base of the lithosphere and subduction related flows with possible contributions from the crust. Using direct S-waves in splitting measurements we obtain additional measurements that provide new constraints in regions with complex anisotropy.

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10 – 12 MARCH 2016

POSTER

Seismic Anisotropy Beneath Anatolian Plate from SK(K)S Splitting

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Anatolian plate has complex tectonic history that deserves a thorough study. The interaction between lithospheric structures and mantle flow provide key questions on the information of mantle dynamics, particularly in continental areas. Upper-mantle deformation is an important objective of mantle tectonics. Such mantle deformation can be mapped using seismic anisotropy obtained from the splitting analysis of vertically propagating SK(K)S waves. In this thesis work, we analyzed the upper-mantle anisotropy beneath the Anatolian plate by measuring the teleseismic splitting of seismic core phases. The measured splitting parameters are the azimuth of the fast split shear-wave polarization and the delay time between the two split shear-waves. We investigated the present and past deformation processes beneath the Anatolian plate with obtained splitting parameters. To make a systematic mapping of upper-mantle anisotropy in the Anatolian plate, we used earthquake data from 394 broadband stations of various permanent and temporary networks. We attained 3423 good and fair splitting measurements and 3336 null splitting measurements. The maximum anisotropy magnitude is located beneath the Western Anatolia, Marmara region and Eastern Anatolian Plateau. Our results suggest that the anisotropy is likely to be dominated by sublithospheric mantle deformation. We propose that the observed anisotropy can be explained by active mantle flow around the subducting lithosphere beneath Anatolian plate. This research is supported by the Scientific and Technological Research Council of Turkey (TÜBİTAK- Grant number 111Y190).

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POSTER

Neotectonic Evolution of Anatolia: Comparison of Geodynamical Models and Observations

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The neotectonic evolution of Anatolia is dominated by collisions of irregular continental fragments and accretion of island arcs in conjunction with the Alpine orogenesis. Currently, two contrasting tectonic regimes are thought to prevail the Anatolian plate: (1) western Anatolia and the adjacent Aegean region is marked by back-arc rifting (e.g., normal faulting, exhumational zones, subsidence) due to the Hellenic slab retreat/roll back since the late Oligocene-Early Miocene times; and (2) Eastern Anatolia is deformed by compressional tectonics (e.g., thrust faults, fold-thrust belts, uplift) associated with the northward motion of the Arabian plate. Seismological studies suggest that an entire Anatolian lithosphere may not be thicker than 100 km (inferred by anomalously slow P and S wave velocities) in which some portions of the mantle lithosphere may be removed and is replaced by the upwelling of hot asthenospheric mantle. In this work, we first review the proposed geodynamic scenarios to account for the anomalous surface tectonics and then investigate the role of mantle dynamics that presumably drives transient vertical motions along the Anatolian plate. Our numerical predictions show that the East Anatolian plateau uplift (>2 km, since the Early Miocene) may be driven by the combination of the slab removal and the northward Arabian plate convergence. Furthermore, synchronous with the plateau uplift, thermo-petrological model results show that the decompression melting of the asthenospheric mantle while uprising and the partial melting of the subducting slab produce magmatism in both alkaline and calc-alkaline chemistry in the middle section of the plateau (near Van region). Geodynamic models investigating the amount of back-arc extension induced by slab retreat suggests ~ 300 km slab retreat and > 1.5 km of surface subsidence in the Aegean-western Anatolia back-arc. Model calculations controlled by varying visco-plastic rheological characteristics of the subducting ocean and continental lithosphere are in good agreement with the HP/LT P-T-t patterns for the exhumed metamorphic massifs of western Anatolia.

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POSTER

Millennial Strain Partitioning and Fault Interaction Revealed by ^{36}Cl Cosmogenic Nuclide Datasets from Abruzzo, Central Italy

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In zones of distributed continental faulting, it is critical to understand how slip is partitioned onto brittle structures over both long-term millennial time scales and shorter-term individual earthquake cycles. The comparison of slip distributions on different timescales is challenging due to earthquake repeat-times being longer or similar to historical earthquake records, and a paucity of data on fault activity covering millennial to Quaternary scales in detail. Cosmogenic isotope analyses from bedrock fault scarps have the potential to bridge the gap, as these datasets track the exposure of fault planes due to earthquakes with better-than-millennial resolution. In this presentation, we will use an extensive ^{36}Cl dataset to characterise late Holocene activity across a complicated network of normal faults in Abruzzo, Italy, comparing the most recent fault behaviour with the historical earthquake record in the region.

Extensional faulting in Abruzzo has produced scarps of exposed bedrock limestone fault planes that have been preserved since the last glacial maximum (LGM). ^{36}Cl accumulates in bedrock fault scarps as the plane is progressively exhumed by earthquakes and thus the concentration of ^{36}Cl measured up the fault plane reflects the rate and patterns of slip. In this presentation, we will focus on the most recent record, revealed at the base of the fault. Utilising new Bayesian modelling techniques on new and previously collected data, we compare evidence for this most recent period of slip (over the last several thousands of years) across 5-6 fault zones and with the historical record. We demonstrate that the rate of slip on individual fault strands varies significantly, between having periods of accelerated slip to relative quiescence. Where data is compared between across-strike fault zones, it appears that slip is partitioned such that one fault zone takes up a significant portion of strain across the region for hundreds to thousands of years.

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POSTER

Seismological and Structural Features of 9 November 2011 Earthquake, M_w 5.6, in Edremit-Van (Eastern Turkey)

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23th of October, 2011 Van Earthquake (M_w 7.1) showed that Van Lake basin is located in the Bitlis-Zagros Thrust Fault Belt and surrounded by active structural elements of tectonic system developed by a N-S trending continental-continental collision. November 9, 2001 (M_w=5.6) occurred on an intra-plate strike-slip fault plane that was formed by a compressional system. Fault mechanism solutions reported by different seismological agencies indicate also strike slip fault mechanism. Focal mechanism solutions of Edremit Earthquake aftershocks also indicate strike-slip fault mechanism. The fault plane known as Edremit Fault starts from Beyüzümü village located NE of the Van city and continues to Edremit town located SW of the Van city. The total length of the fault is about 19 km. Seismogenic zone is about 8 km on the Edremit Fault and the fault strike varies from 200° to 215°, and the fault dip changes from 70° to 80°. The Edremit Fault controlling and deforming the Plio-Quaternary lacustrine deposits with lateral transition river deposits around Beyüzümü village allows deposition of travertines around Edremit town in SW. The Edremit fault has been also deforming these travertines. In this study, present day stress distribution of conjugate faults and striations in the Plio-Quaternary deposits obtained using the fault plane solutions determined from main shock and aftershock sequences. Our results suggest that the continental crust between Beyüzümü and Edremit in the Lake Van basin is compressed in NW direction (σ_1) and tensioned in NE direction (σ_3) by the left lateral strike slip Edremit fault. According to these results, stress distributions are complex and show differences depending on active fault planes in the Lake Van basin deformed by the active compressional tectonic system.

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POSTER

Morphologic and Seismic Features in the Gulfs of Gökova, Marmaris and Fethiye, SW Turkey

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The submarine morphological and seismic features in the gulfs of Gökova, Marmaris and Fethiye were investigated by multi-beam bathymetric, single channel and multi-channel seismic reflection data respectively in terms of the currently still active regional tectonic setting. The deformation onshore in SW Turkey is dominated by crustal extension. However, in the offshore area there are considerable evidence of active strike-slip faulting has been observed in this study.

Structurally, the folds and faults with strike-slip and reverse components have been regionally mapped in the Gulf of Gökova. Of these, NE–SW-oriented left-lateral strike-slip faults with compressional components forming the so-called Gökova Fault Zone intersect and displace two WNW–ESE-oriented submarine ridges and deep submarine plains. Thus, strike-slip faults are the youngest major structures in the gulf, and control present-day active tectonics. However, some E–W-oriented normal faults occur on the northwestern and partly also southern shelf, and along the borders of the adjacent deep submarine plains of the Gulf of Gökova. They are intersected and displaced by the strike-slip faults. The lower seismicity along the normal faults relative to the NE-SW oriented strike-slip faults suggests that the former are at present inactive or at least less active.

The bathymetric data indicates, a submarine plain between the island of Rhodes and Marmaris Gulf, and a large canyon connecting the abyssal floor of the Rhodes Basin with Fethiye Gulf which were named as the Marmaris Plain and Fethiye Canyon, respectively. Several active and inactive faults have been identified. Inactive faults delineate a buried basin beneath the Marmaris Plain, and referred to as the Marmaris Basin. Other faults that affect all stratigraphic units are interpreted as being active. The NE-SW-oriented Marmaris Fault Zone located on the Marmaris Plain is interpreted as a transtensional fault zone in the seismic and bathymetric data. Another important fault zone occurs along the Fethiye Canyon, forming the northeastern extension of the Pliny Trench and the transpressional character of these faults inferred from the seismic data is well correlated with the compressional structures along the Pliny Trench in the Rhodes Basin and its vicinity. These observations suggest that the Marmaris Fault Zone have evolved independently of faults of Fethiye Canyon. Moreover, the relation of these faults with Fethiye-Burdur Fault Zone onland deserves further detailed studies. In summary, NE–SW-oriented strike-slip faults were mapped as major tectonically active features in the Gulfs of Gökova, Marmaris and Fethiye suggesting that strike-slip faulting may be of greater importance in this region than previously thought.

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10 – 12 MARCH 2016

POSTER

East Anatolian Plateau Underlain Largely by a Continental Crust Rather than Oceanic Accretionary Complex

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The Eastern Anatolian high plateau, ~2000 m above sea level, is characterized by (i) an average crustal thickness of ca. 45 km, (ii) a nonexistent or very thin lithospheric mantle and (iii) an immense Neogene-Quarternary volcano-sedimentary cover. Its basement is commonly thought to consist of wholly of an oceanic accretionary complex of Late Cretaceous to Oligocene age. Widespread Neogene-Quaternary magmatism is commonly ascribed to slab steepening and break-off. We herein describe two metamorphic domains (the Akdağ and Taşlıçay areas) separated from each other by ~150 km, beneath the Neogene-Quaternary volcanic cover.
They are made up of (i) upper amphibolite- to granulite facies marble, and subordinate amphibolite/pyroxenite, migmatitic to restitic metapelite and metagranite, equilibrated at ~800˚C and 6 kbar. Timing of high-temperature/low to medium pressure metamorphism is constrained as Late Cretaceous (90 ± 2 Ma; 2s) by U-Pb dating on metamorphic zircon. The metamorphic rocks were pierced by coeval gabbroic to granodioritic intrusions. Both the metamorphic rocks and the intrusions were in turn obducted by the ophiolitic rocks by Late Campanian-Maastrichtien time.
Several lines of evidence such as (i) absence of obviously oceanic rock types, and presence of metagranites and amphibolites with anorogenic alkaline affinity in the metamorphic rock assemblage, (ii) absence of any indication for high-pressure metamorphism and (iii) clearly obducted nature of ophiolitic rocks consistently indicate that the East Anatolian plateau under the young volcano-sedimentary cover is underlain by a continental crust, rather than oceanic accretionary complex. Late Cretaceous low-pressure/high temperature metamorphism and coeval magmatism are interpreted to have occurred at the middle to lower crustal depths of a Late Cretaceous magmatic arc probably related to the northward subduction along the Bitlis suture.

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POSTER

Present-Day Dynamic Topography in Eastern Anatolia

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The Eastern Anatolian Plateau with ~2 km topography developed in the last 10 Myr and formed at the same time as ongoing westwards extrusion of the Anatolian block and shortening due to ongoing continental-continental collision of Arabian and Eurasian plates. The region contains widespread volcanic rocks formed through mantle upwelling production, and shallow Curie-point depth and high surface heat flow values characterize the upper crust. Seismological observations indicate relatively high Pn and Sn attenuation and significant low seismic velocity anomalies beneath the region. The observed topography cannot be supported by crustal thickness (only ~45 km in the region) based on the principle of Airy isostasy. Based on these observables, we propose that there is active dynamic topography supporting uplift of the Eastern Anatolian Plateau. We conducted 2D thermo-mechanical models to explain present-day dynamic uplift driven by 3-D upper mantle flow in Eastern Anatolia. P-wave tomography data extracted along 10 profiles were used to obtain depth-dependent density anomalies in the region. We compared our findings with other independent datasets concerning geological deformation and dynamic topography predictions. The results indicate an upper mantle driven dynamic uplift correlated with the under-compensated topography in Eastern Anatolia. We discuss our results combined with 3D mantle flow by considering seismic anisotropy studies in the region. According to our initial results the localized low Pn velocities and Pn anisotropy structures show nearly spatial coherence with high dynamic uplift in Eastern Anatolia.

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POSTER

Observations and Numerical Simulation of 28 October 2012 Earthquake, M_w 7.8, and the Tsunami in Queen Charlotte Islands, British Columbia

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In this study, simulation of tsunami-waves generated by the 28 October 2012 Queen Charlotte Islands earthquake (M_w 7.8) is investigated. The Queen Charlotte Island region is known as one of the most seismically active areas in British Columbia (Canada). Destructive earthquakes in the region appear to be controlled by active tectonic features that have been developed in response to the convergent movements of Pacific and Juan De Fuca Plates, subducting beneath the North American Plate. Early studies suggest that plate motions are dominantly taken up by strike-slip faulting parallel to the plate boundary. However, the October 28, 2012 earthquake occurred as a result of oblique thrust faulting with a best double-couple fault mechanism of strike: 325°, dip: 25°, rake 100°, and confirmed M_w 7.8 with a seismic moment of 3.86×10^{20} Nm. The finite-fault slip distribution of this earthquake is estimated from a back-projection method in which teleseismic broad-band P-waveforms are used to integrate the direct P-phase with reflected phases from structural discontinuities near the source. The earthquake caused the largest local tsunami striking coastal plains of British Columbia with run-up heights up to maximum 12.98m, 8.45m, 4.50m, and 7.41m in Davidson Inlet, Gilbert, Goski, and Gudal Bays (British Columbia), respectively, which are directly measured from watermarks on trees, buildings and walls reported by National Geophysical Data Center (NGDC-NOAA). Numerical simulations of tsunami wave propagation are conducted by using nonlinear long-wave equations on spherical coordinates. The governing equations are discretized with the explicit leap-frog finite difference scheme. Within the spatial domain, entire simulation area is covered at a resolution of 0.5 minutes by GEBCO30 bathymetry data. Non-uniform rupture of the fault based on finite fault slip distribution modeling is considered to estimate sea-bed displacement. The ocean bottom displacement that is assumed to be responsible for the initial water surface deformation give rises to the tsunami waves, and is computed using the elastic dislocation algorithm from the preferred finite-fault slip model. As an initial height of tsunami, the vertical displacement of water surface is assumed to be the same as ocean bottom displacement. We computed the maximum vertical sea floor dislocations with uplift of 1.82m and subsidence of 0.1m, respectively. The results of tsunami simulations are compared with the 7 tide gauges and 6 Deep-ocean Assessment and Reporting of Tsunami (DART) buoy records. De-tiding, de-trending, low-pass and high-pass filters were applied to detect tsunami waves in deep ocean sensors and tide gauge records. Simulation results and observed records showed that 28 October 2012 earthquake generated about 1m-height tsunami in Maui, Hilo (Hawaii), arriving about 5 hours and 30 minutes after the earthquake. Overall, our results likely contribute to determination of tsunamigenic coastal regions by simulating locations, arrival times, amplitudes, and direction of tsunami waves that are consistent with observed records.

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POSTER

Seismic History of the Cnidus Fault Zone: Inferences from Cosmogenic ^{36}Cl Surface Exposure Dating of the Fault Scarp

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Cnidus, one of the largest cities of the antique times was built on hill slopes formed by several normal faults on a Datca peninsula located in SW Turkey. The Datça Peninsula defines southern boundary of the Gulf of Gökova and also Western Anatolian Extensional Province. The seismic history of the Cnidus Fault Zone is therefore may provide insights about fault activity covering millennial scale to Pleistocene scale in the southern Aegean Region. Our investigation relies on cosmogenic 36Cl surface exposure dating method on normal faults scarps in limestone. This method is a powerful tool to reconstruct seismic history of normal faults and critical to understand regional seismic hazard. We focus on one of the most prominent fault scarp (hereinafter Mezarlık Fault) stretching along the antique Cnidus city. We collected 128 pieces of tablet size (10x20cm) and 3 cm thick samples along the wall of the scarp and also opened conventional paleoseismic trenches at the base of the fault scarp. Our 36Cl concentration profile indicates 3 may be 4 events associated with the Mezarlık Fault since Last Glacial Maximum (LGM). Our results from paleoseismic trenching are also compatible with 36Cl results indicating 3 or 4 events that disturbed colluvium deposited at the base of the scarp. Here we will present implications for seismic history and slip rate associated with the Mezarlık Fault.

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10 – 12 MARCH 2016

POSTER

Finite-Fault Slip Distribution Model and Tsunami Simulation of The 16 September 2015 Earthquake, M_w *8.3,* in Illapel (central Chile)

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A massive, M_w *8.3*, earthquake struck the region of Illapel (central Chile) on 16 September 2015 (t_o: 22:54:32 UTC, USGS), and caused high amplitude tsunami waves reaching more than 3 meters. In this study, we determined earthquake source mechanism parameters using teleseismic long-period P- and SH- and broad-band P-waveforms recorded by the Federation of Digital Seismograph Networks (FDSN) and the Global Digital Seismograph Network (GDSN) stations. We compared the shapes and amplitudes of waveforms, recorded in the distance range of 30°- 90°, with synthetic waveforms. Finite-fault slip distribution on the fault plane of September 16, 2015 Chile earthquake is further determined by applying a new back-projection method that uses teleseismic P-waveforms to integrate the direct P-phase with reflected phases from structural discontinuities near the source. In slip inversion, we assumed that faulting occurs on a single fault plane (strike and dip angles are taken from the minimum misfit point-source solution), and slip (rake) angle varied during the rupture process. The fault length and fault width, average and maximum displacements on fault plane, rupture duration and stress drop value are calculated by using the preferred finite-fault slip model. Furthermore, numerical simulations of tsunami wave propagations caused by September 16, 2015 Chile earthquake have been implemented, and the results are compared with tide gauges and Deep-Ocean Assessment and Reporting of Tsunami (DART) buoy records. The GEBCO30 bathymetry data and non-linear shallow water equations, solved with a finite difference scheme, are used in tsunami wave simulations.

Teleseismic P- and SH- waveform inversion results exhibited that the 2015 Illapel (central Chile) earthquake occurred as a result of thrust faulting mechanism with a best double-couple of N-S directed fault plane (strike: 350°, dip: 25°, rake: 80°), and a shallow focal depth of 26 km. However, preferred finite-fault slip model revealed rupture propagation mainly along dip direction of the fault plane with an area of maximum slip (6.50m) at NW of the centroid. We further observed that the amplitudes and arrival times of tsunami waves, acquired by numerical tsunami simulations, are coherent with the DART buoy records and tide gauges except only two stations.

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