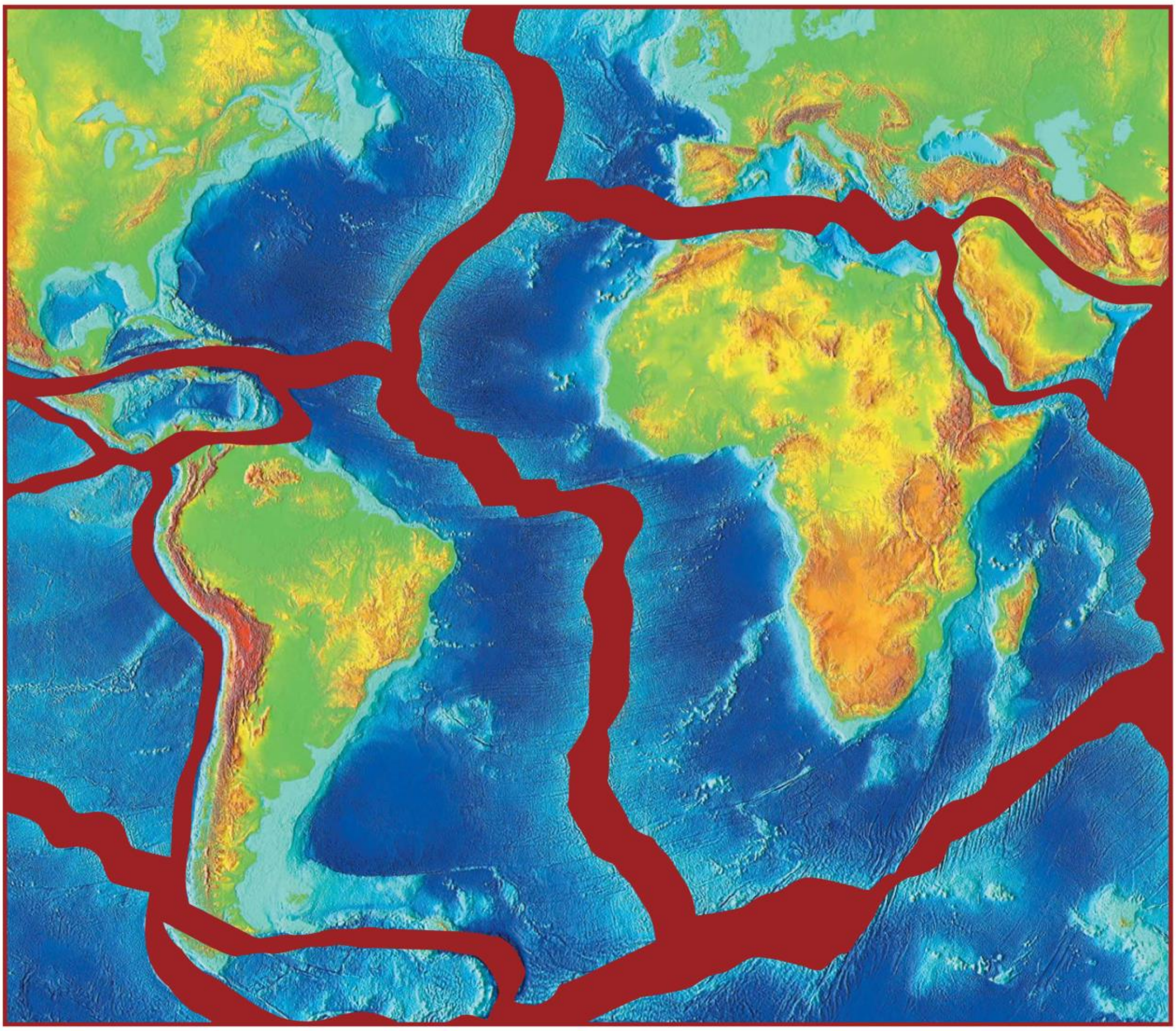
European Geosciences Union

GIFT – Geosciences Information For Teachers



# GIFT 2019

## PLATE TECTONICS AND EARTH'S STRUCTURE YESTERDAY, TODAY, TOMORROW

Vienna, Austria, 8-10 April 2019

Dear Teachers,

A very warm welcome to our 26th Geosciences Information for Teachers (GIFT) workshop/ conference. Over the years, GIFT has become an integral part of the European Geosciences Union (EGU) General Assembly and we are very glad that EGU puts such high priority on education, allowing us all to benefit.

This year we are in for a real treat as we explore together 'Plate tectonics, yesterday, today and tomorrow'. We welcome global experts in different aspects of plate tectonics as well as experienced providers of professional development in geoscience classroom teaching.

Our programme this year includes the following:

- A welcome from our EGU President, Jonathan Bamber from Bristol University in the UK and by EGU Vice-President Alberto Montanari, from the University of Bologna, Italy. They have promised to be there!
- We begin our presentations with a focus on the big plate tectonic picture, from yesterday, today and tomorrow. We are privileged indeed to have with us one of the founders of plate tectonic theory, Xavier Le Pichon from Collège de France, France who will introduce us to the early thinking about plate tectonics and how this word-changing theory evolved. Xavier will also be presenting an open lecture later in the General Assembly, to which you are all invited. In the next presentation, Carlo Laj, a key member and past chair of the EGU Committee on Education and a member of the École Normale Supérieure PSL Research University in France will remind us of the remarkable story of how the magnetic anomalies over ocean ridges were found and contributed to our understanding of sea floor spreading, giving us particular insights from Fred Vine, one of the key contributors. Finally, in this first section, an update on our current understanding of plate tectonic and its global importance will be provided by Onno Onken from the GFZ, the German Research Centre for Geosciences in Potsdam, Germany.
- In our next section, we will be introduced to current thinking on the links between plate movements and earthquake activity by Jean-Philippe Avouac from the California Institute of Technology in Pasadena, USA, then Christophe Vigny from the Ecole Normale Supérieure/CNRS in Paris France will help us to explore the origin of earthquakes in the stable areas away from plate margins.
- Further modern perspectives on plate tectonics will begin with a focus on seafloor spreading presented by Mathilde Cannat from the Institut de Physique du Globe de Paris in France. Then some of the key evidence for plate tectonics now and in the past from imaging the deep Earth will be presented by Barbara Romanowicz from the Collège de France in Paris and the University of California, Berkeley, USA. The links between Earth's surface geology and Earth's deep interior will be explored by Clinton P. Conrad from the University of Oslo, Norway and then the impacts of plate tectonics on climate, with the perspectives it provides on modern climate change discussions, will be discussed by Gilles Ramstein from the Laboratoire des Sciences du Climat et de l'Environnement, in Gif-sur-Yvette, France.
- The Corinth Rift in Greece is one of the most seismically active areas in the world and it is bridged by the Rion-Antirrion Bridge. Akis Panagis from the Structural Department of the Rion Antirrion Bridge will explain how the bridge was designed to withstand earthquakes and how all the sensors on the bridge make it one of the most sensitive seismic instruments on Earth.
- Francesco Sarti, a long-time friend of GIFT Conferences, will present satellite data perspectives on plate tectonic movements today and their applications.

- To bring all our discussions together, possible developments of plate tectonics in the future will be debated by Nicholas Coltice from the École Normale Supérieure PSL Research University as we think about how the future Earth might develop.
- A series of hands on teaching activities will be provided at different stages of the workshop by members of the Committee on Education including Jean-Luc Berenguer, who will explore the plate tectonic model using maps and data, Stephen Macko who will present a novel way of teaching the relationship between seafloor spreading and magnetic reversals, and Chris King who will present a workshop on plate tectonics and a session on outdoor Earth science-teaching activities.
- We will be provided with updates from EGU's own Media and Communications Manager, on the educational insights provided by Planet Press; by Giuliana D'Addezio from the National Institute for Geophysics and Volcanology in Rome, Italy, on the Envriplus H2O2O educational project and the Envrigame; and by Teresita Gravina from the EGU CoE on the teaching opportunities provided by Scientix and Europeana.
- Herbert Summesberger (CoE) together with his colleague Mathias Harzhauser will offer us all a memorable opportunity to visit the Natural History Museum Vienna, one of the most famous natural history museums in the world (https://www.nhm-wien.ac.at/en), on the Sunday afternoon before the conference. Herbert also offers an opportunity for us to join him on a geological trail from Maria Theresa's Monument to St. Stephen's Cathedral in central Vienna on the Wednesday afternoon after GIFT has concluded.

The GIFT workshop is sponsored not only by EGU, but also by several science organizations. We would like to continue to offer teachers the opportunity to attend GIFT and similar workshops, but this depends upon us being able to show our sponsors that teachers have used the GIFT information and educational approaches in their daily teaching, or as inspiration for teaching geoscience in new ways in their schools.

**Therefore, we ask you:**

1. To complete the evaluation forms as soon as possible and email them back to us;
2. To make a presentation of your experiences of GIFT to a group of your teaching colleagues sometime after you return from EGU, and
3. To send us reports and photographs about how you have used the GIFT information in your classrooms. We also encourage you to write reports on the GIFT workshop in publications specifically intended for geoscience, science and geography teachers.

Information on past GIFT workshops is available here:
http://www.egu.eu/education/gift/workshops
where you can find the brochures (pdf) and the slides of the different presentations given at the GIFT workshops over the past 13 years. Since 2009, we have also included web-TV presentations, which may be freely downloaded and used in your classrooms. By clicking on http://www.egu.eu/education you will find out about all the educational activities of the European Geosciences Union.

So, we are all being offered a feast of educational experiences and opportunities and many ideas, experiences and activities to share with one another and with our classes when we get home. Do please enjoy yourself, your contacts with teachers from around the world and the many opportunities offered by the GIFT Conference and the General Assembly. Even more, please tell your friends and colleagues about the EGU and GIFT and encourage them to join us at future GIFT conferences. Finally, but very importantly, if you are using social media, please tag your posts or pictures @Eurogeosciences #GIFT2019 #EGU19.

*The Committee on Education*
*European Geosciences Union*

# Acknowledgements

The GIFT-2019 workshop has been organized by the Committee on Education of the European Geosciences Union. EGU has provided the major share of the expenses, but the workshop has also benefited from the generous help of:

Future Ocean, Kiel Marine Science

Westermann Verlag, Braunschweig, Germany

Natuaral History Museum
Vienna

And we thank all the speakers who have contributed to this educational workshop and their institutions!

# Committee on Education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**Herbert Summesberger**
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Austria
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# Committee on Education

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Jean-Luc Berenguer

Francesca Cifelli

Gordon Curry

Francesca Funiciello

Teresita Gravina

Chris King

Konstantinos Kourtidis

Carlo Laj

Steve Macko

Helder Pereira

Annegret Schwarz

Phil Smith

Herbert Summesberger

# *Program*

*European Geosciences Union – General Assembly*

*GEOSCIENCE INFORMATION FOR TEACHERS (GIFT) WORKSHOP*

*Vienna, 8-10 April 2019*

# *'Plate Tectonics and Earth's Structure Yesterday, Today, Tomorrow'*

## Sunday April 7, 2019

| | |
|---|---|
| 16:00-18:00 | **GUIDED TOUR OF THE NATURAL HISTORY MUSEUM VIENNA**<br>Herbert Summesberger and Mathias Harzhauser<br>Natural History Museum Vienna, Austria |
| 18:30-20:00<br>(optional) | Ice breaker party at Austria Center Vienna |

## Monday April 8, 2019

| | |
|---|---|
| 8:30-08:45 | **WELCOME**<br>Jonathan Bamber<br>*Outgoing President of EGU*<br>Alberto Montanari<br>*Incoming President of EGU*<br>Chris King<br>*Chair of the CoE* |

*Chairpersons: Chris King and Carlo Laj, EGU Committee on Education*

| | |
|---|---|
| 8:45-9:30 | **FIFTY YEARS OF PLATE TECTONICS, AFTERTHOUGHTS OF A WITNESS**<br>Xavier Le Pichon<br>*Collège de France, Paris, France* |
| 9:30-10:15 | **MAGNETIC ANOMALIES OVER OCEANIC RIDGES**<br>***(In the footsteps of Frederic Vine)***<br>Carlo Laj<br>*Ecole Normale Supérieure, Paris, France*<br>*EGU Committee on Education* |
| **10:15 – 10:45** | **COFFEE BREAK** |

*Chairperson: Friedrich Barnikel, EGU Committee on Education*

| | |
|---|---|
| 10:45-11:30 | **PLATE TECTONICS: A GEOLOGICAL PERSPECTIVE**<br>Onno Oncken<br>*GFZ, Potsdam, Germany* |

11:30-12.15 **IMAGING THE DEEP EARTH**
Barbara Romanowicz
*Collège de France, Paris, France*
*University of California, Berkeley, USA*

12:15-12:25 **INSTRUCTIONS FOR THE POSTER SESSION EOS 1.3**
Eve Arnold
*EGU Committee on Education*

12:25-12:35 **PLANET PRESS**
Bárbara Ferreira
*EGU Media and Communications Manager*

12:35-12:45 **ENVRIPLUS E-LEARNING PLATFORM**
Giuliana D'Addezio and Marina Longhitani
*INGV, Rome, Italy*

**12:45-13:30 LUNCH (SANDWICHES)**

*Chairperson: Jean-Luc Berenguer, EGU Committee on Education*

13:30-17:00 **HANDS-ON ACTIVITIES** (two groups alternating)

Group 1 **EXPLORING PLATE TECTONIC MODELS WITH DATA AND MAPS**
Jean-Luc Berenguer
*EGU Committee on Education*

Group 2 **THE STRUCTURE OF THE EARTH AND PLATE TECTONICS**
Chris King
*EGU Committee on Education*

**17:00 TOUR OF THE EGU EXHIBITION**

## Tuesday April 9, 2019

*Chairperson: Phil Smith, EGU Committee on Education*

8:30-9:15 **PLATE TECTONICS: THE ORIGIN OF EARTHQUAKES IN AND AROUND STABLE PLATES**
Christophe Vigny
*Ecole Normale Supérieure/CNRS, Paris, France*

9:15-10:00 **OVERVIEW ON SEAFLOOR SPREADING**
Mathilde Cannat
*CNRS-Institut de Physique du Globe de Paris, France*

10:00-10:10 **SCIENTIX AND EUROPEANA: ONLINE RESOURCES TO TEACH EARTH SCIENCES**
Teresita Gravina
*EGU Committee on Education*

**10:10-10:45 COFFEE BREAK (and GIFT 2019 GROUP PICTURE!)**

*Chairperson: Francesca Funiciello, EGU Committee on Education*

10:45-11:30 **PLATE TECTONICS AND EARTHQUAKES**
Jean-Philippe Avouac
*California Institute of Technology, Pasadena, USA*

11:30-12:15 **PLATE TECTONICS: LINKING SURFACE GEOLOGY TO EARTH'S DEEP INTERIOR**
Clinton P. Conrad
*University of Oslo, Norway*

12:30-13:00 **HANDS-ON ACTIVITIES** (two groups alternating)

(GROUP 1) Earth Science around the Austria Center Vienna
Chris King
*EGU Committee on Education*

(GROUP 2) Demonstrating the linkage of Sea Floor Spreading to Paleomagnetism/ Magnetic Reversals in support of the theory of Plate Tectonics
Stephen Macko
*EGU Committee on Education*

**13:00-13:30 LUNCH (SANDWICHES)**

13:30-14:00 **HANDS-ON ACTIVITIES** (two groups alternating)

(GROUP 1) Demonstrating the linkage of Sea Floor Spreading to Paleomagnetism/ Magnetic Reversals in support of the theory of Plate Tectonics
Stephen Macko
*EGU Committee on Education*

(GROUP 2) Earth Science around the Austria Center Vienna
Chris King
*EGU Committee on Education*

*Chairperson: Eve Arnold, EGU Committee on Education*

14:00-15:45 **EOS 1.3 – POSTER SESSION**

**15:45-16:15 COFFEE BREAK**

16:15-18:00 **EOS 1.3 – POSTER SESSION**

18:00-19:00 **NETWORKING EVENT IN THE POSTER HALL WITH BEER!**

## Wednesday April 10, 2019

*Chairperson: Annegret Schwarz, EGU Committee on Education*

8:30-9:15 **PLATE TECTONICS AND CLIMATE**
Gilles Ramstein
*CEA-LSCE, GIF-SUR-YVETTE, FRANCE*

9:15-10:00 **BRIDGING THE RIFT, EARTHQUAKE DESIGN OF THE RION-ANTIRRION BRIDGE**
Akis PANAGIS
*Structural Department of Rion Antirrion Bridge, Patras, Greece*

10:00 - 10:15 **GIFT POSTER CERTIFICATES DISTRIBUTION**

**10:15-10:45 COFFEE BREAK**

*Chairperson: Stephen Macko, EGU Committee on Education*

10:45-11:30 **USE OF SATELLITE DATA (EARTH OBSERVATION AND NAVIGATION) FOR PLATE TECTONICS APPLICATIONS**
Francesco Sarti
*ESA, Frascati, Italy*

11:30- 12:15 **SOME SHAPES OF PLATE TECTONICS TO COME**
Nicolas Coltice
*Ecole Normale Supérieure, Paris, France*

12:15- 13:00 **GENERAL SESSION AND CONCLUDING REMARKS**

**13:00 LUNCH (SANDWICHES)**

**GOOD BYE!**

***Optional:***
14:30-16:00 **GEOLOGICAL TRAIL FROM MARIA THERESA'S MONUMENT TO ST. STEPHEN'S CATHEDRAL**
Herbert Summesberger
*Natural History Museum Vienna, Austria*

# *Speakers*

# GUIDED TOUR OF THE NATURAL HISTORY MUSEUM VIENNA

**Herbert Summesberger and Mathias Harzhauser**
Natural History Museum Vienna

Standing on each side of the bronze elephant (an artwork of the Viennese artist Gottfried Kumpf) in front of the entrance, our two hosts for the visit to the Natural History Museum Vienna:

**Mathias Harzhauser**, on the left, Head of the Department of Geology and Palaeontology, has earned his degrees from the University of Vienna and has been employed by the NHM after his Master's thesis. His PhD thesis deals with the Palaeoceanography of the Oligocene and Lower Miocene Gastropoda of the Eastern Mediterranean and the Western Indo-Pacific.

**Herbert Summesberger**, on the right, has earned his degrees from the University of Vienna. His PhD thesis deals with structural geology, stratigraphy and palaeontology in the Northern Calcareous Alps. He has organized several international symposia and is the leader of the Working Group on Geosciences, School and Public Relations of the Austrian Geological Society. Retired since 2004, he is a member of the Board of the Friends of the Museum of Natural History, and organizes exhibitions and seminars for High School teachers. He has also written high school books and a Vienna city guide for building and decoration stones.

**Xavier Le Pichon**
Collège de France
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**Career**
Emeritus Professor, Chair of Geodynamics, Collège de France, Paris
Member French and US Academies of Sciences
Plate Tectonics
First global kinematic model of plates in 1968

**Educational activities and Honors:**
Japan Prize, Balzan Prize, Grand Prix Gaudry, Wegener Medal, Wollaston Medal, Maurice Ewing Medal

**Present research:**
Formation of the Eastern Mediterranean, Origin of Hellenic subduction, Pangea and Lower Mantle.

# FIFTY YEARS OF PLATE TECTONICS AFTERTHOUGHTS OF A WITNESS

**Xavier Le Pichon**
Collège de France, Paris, France

My presentation will not be the exhaustive history of an unbiased outside observer. It will just be the report of one of the participants who interacted with quite a few of the main actors of this revolution. Fifty years later, I revisit these extraordinary times. I argue that the Earth Sciences in the mid-1950s entered a state of supercooling where the smallest input could lead to the simultaneous crystallization of new ideas. I joined in 1959 the Lamont Geological Observatory, one of the hotbeds where the Plate Tectonic revolution germinated. I emphasize the state of confusion and contradiction but also of extraordinary excitement in which we, earth scientists, lived at this time. I identify several cases of what I consider to be simultaneous appearances of new ideas and describe what now appears to be incomprehensible failures to jump on apparently obvious conclusions, based on my own experience. Finally, I propose that we are within a similar supercooled state that precedes a new era of geodynamics where the link between plate tectonics and deeper tectonics of the whole Earth will become obvious.

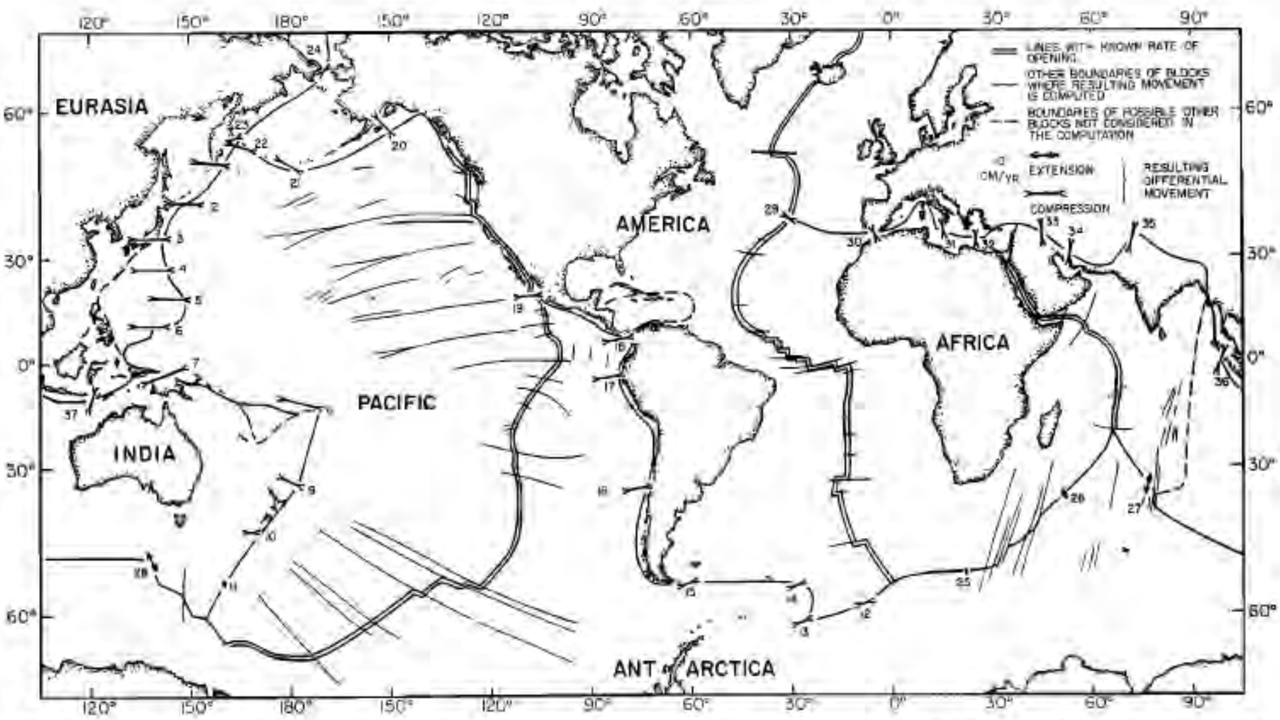


Fig. 6. The locations of the boundaries of the six blocks used in the computations. The numbers next to the vectors of differential movement refer to Table 5. Note that the boundaries where the rate of shortening or slippage exceeds about 2 cm/yr account for most of the world earthquake activity.

*See following link for other illustrations*
https://blogs.egu.eu/divisions/ts/2018/11/06/meeting-plate-tectonics-xavier-le-pichon/

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&
Committee on Education
European Geosciences Union

**Education:**
Secondary school in Italy and the USA (American Field Service Exchange Student) University studies at the University of Paris, PhD in Solid State Physics.

**Career**
I have spent all my scientific career as an employee of the French Atomic Energy Commission, first as a researcher in the Physics Department then in the field of geophysics.
In 1985, I was appointed as Deputy Director of the Centre des Faibles Radioactivités and Head of the Department of Earth Sciences. I created and was first director of the Laboratoire de Modélisation du Climat et de l'Environnement, which was later united with the Centre des Faibles Radioactivités to form the present Laboratoire des Sciences du Climat et de l'Environnement (LSCE). After 3 terms as Head of Department (12 years) I stepped down to a researcher position again, until I retired. I have been an "emeritus" researcher since then, and gradually reoriented my activities towards education.

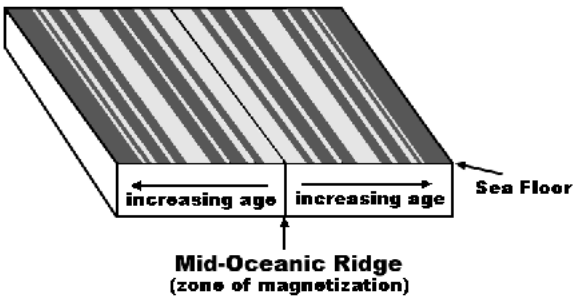
**Research Interests:**
After my PhD I spent a few years working with critical phenomena (scattering of laser light by critical fluids) then moved into the field of geophysics.
My main interests in this new field has always been linked to the magnetic properties of sediments and igneous rocks (paleomagnetism), used with several objectives: geodynamical reconstructions (particularly in the Eastern Mediterranean and the Andean Cordillera), reconstruction of the history of the Earth's magnetic field (including the morphology of field reversals) and more recently reconstructions of environmental and climatic changes on a global scale.
I have published over 200 articles in international scientific journals and a few general popular articles in different journals.
Supervisor of 12 PhD students, and 8 Masters of Science

**Educational activities and Honors:**
Founder and Chairman, Education Committee of the European Geosciences Union
Participant to different National and International Education Committees
Union Service Award for creating the Committee on Education of EGU
Excellence in Geophysical Education Award of the American Geophysical Union
Fellow of the American Geophysical Union (AGU).
F. Holweck prize of the French Academy of Science
Holmes Medalist of the European Geosciences Union
Member of the Academia Europea

**MAGNETIC ANOMALIES OVER OCEANIC RIDGES**
**(In the footsteps of Frederic Vine)**

**Carlo Laj**
Ecole Normale Supérieure, Paris, France
EGU Committee on Education

Today it is universally known that the ocean floor is characterized by a series of « magnetic stripes » extending symmetrically on either side of the mid ocean ridges and this seems a simple and natural consequence of sea floor spreading and geomagnetic reversals, and a scheme such as the one in the figure appears in almost every high school textbook.




But at the time (1963) when Frederick Vine and Drummond Matthews proposed their idea that the conveyor belts (as proposed by Hess) might also act as gigantic tape recorders registering reversals of the polarity of the geomagnetic field in the remanent magnetism of the oceanic crust, this was an entirely new hypothesis[1].

It is fair to say that Lawrence Morley, of the Canadian Geological Survey, has proposed exactly the same idea, unbeknown to Vine and Matthew. But Nature and successively the Journal of Geophysical Research rejected Morley's paper for being too speculative, as virtually no data were presented.

Vine and Matthew's idea was actually so new that it was in general poorly received by the scientific community.

There were several reasons for this. As Frederick Vine himself later wrote[2], this hypothesis actually depended on the reality of three different phenomena: sea floor spreading (as suggested by Hess), reversals of the earth's magnetic field, and the importance of remanent magnetism in the oceanic crust. Not one of these was widely accepted at the time:

Hess's proposition was still discussed, the scale of geomagnetic field reversals was still in its infancy. In addition, it was generally thought at the time that the magnetization of ocean floors was induced, not remanent magnetization, so that magnetic anomalies were thought to originate from changes in magnetic susceptibility.

In 1963, the US Naval Oceanographic Office made an aeromagnetic survey (disclosed in 1966) of the Reykjanes Ridge, chosen because it forms the north extension of the Mid-Atlantic Ridge. This survey, over approximately 400 square kilometers, showed a precise

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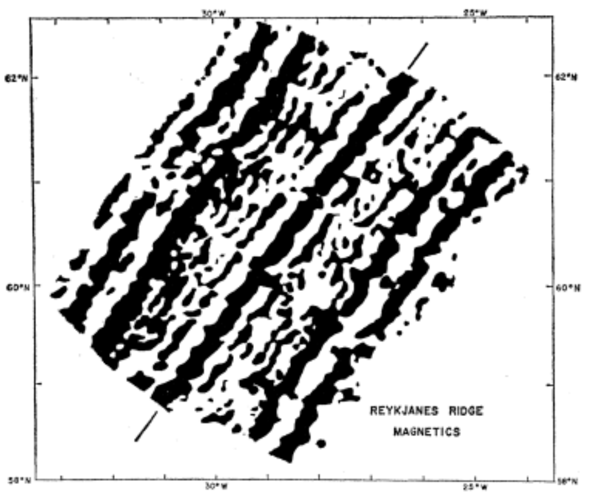
[1] F.J. Vine and D.H. Matthews, (*1963)* Magnetic anomalies over Oceanic Ridges, *Nature, 199, 947-949*

[2] F.J. Vine, *(1966)* Spreading of the Ocean Floor: New Evidence*, Science, 154, 1405-1415*

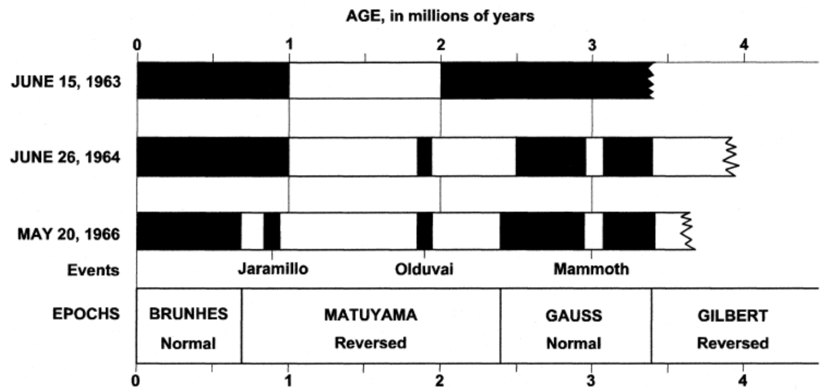
pattern of linear magnetic anomalies symmetrically disposed parallel to the central anomaly.




Later this survey, together with the linearity and symmetrical extension of the magnetic anomalies about other ridges where a magnetic survey was available (the Juan de Fuca, Carlsberg, East Pacific ridges…) provided convincing evidence of the Vine-Matthews hypothesis.

A final, and somewhat important, difficulty subsisted. Correlation of the magnetic anomalies observed at the ridges to the geomagnetic timescale existing at the time (developed by Cox, Doell and Dalrimple at the USGS at Menlo Park) implied major changes in the spreading rate. Although not impossible, this did not appear entirely realistic, for inertial reasons, for a phenomenon occurring on a very broad geographic scale.

It is at this moment (1966) that Doell and Darlymple at Menlo Park, and independently Neil Opdyke at the Lamont Doherty Geological Observatory (LDGO), reported the discovery of a new normal polarity event, named the Jaramillo event, which has occurred between 0.9 and 1.0 million years.




Until the discovery of the Jaramillo event, the narrow magnetic anomalies on either side of the central anomaly had been correlated to the Olduvai event, dated at about 1.8 My. This resulted in an apparent rather slow spreading rate in the recent past. When these same anomalies were correlated to the Jaramillo event, the spreading rates at different ridges appeared quite constant in the last 3.5 My! This was the final proof of the validity of the Vine and Matthews hypothesis.

Later on, Vine himself wrote: "My one regret, as a geologist, was that this detailed record, written within the 60% of the earth's surface covered by oceanic crust, is only available for 4% of the geologic time. Earlier phases of continental drift would have to be deduced from the more complex and fragmentary geological record within the 40% of the Earth's surface covered by continental crust."[3]

[3] Frederick J.Vine, Reversals of fortune, In Naomi Oreskes (Ed.) (2001) *Plate Tectonics: An Insider's History of the Modern Theory of the Earth* (pp 46-66). Westview Press.

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**Education**

1983-1988 Habilitation in Geology (University Frankfurt)
1980-1982 Dr. rer. Nat. in Geology (University Köln)
1975-1980 Diploma in Geology (University Köln)

**Career**

2004-present Director of Department *Geodynamics* and Program Speaker of GFZ
1994-present Full Professor of Geology (Free University Berlin)
1992-present Head of section, GFZ Potsdam
1989-1992 Associate Professor for Geology (University Würzburg)
1983-1989 Assistant Professor (University Frankfurt)
1982-1983 Postdoc (University Münster)

**Research interests**

- dynamic processes shaping convergent margins and mountain belts
- integration of field-based studies with geophysical and geodetic imaging
- physical process simulation
- kinematic evolution of tectonic structures from the earthquake cycle to the long-term

**Publications and Services**

- 1993-1999 Co-chair of priority program 'Orogenic processes' by German Science foundation
- 1994-1997 Project leader of national German reflection seismic program (DEKORP; BMBF)
- 2003-2007 Speaker of the German national 'Continental Margins' project TIPTEQ and member of international INTERMARGINS committee
- Coordinator of international plate boundary observatory Chile (IPOC)
- Speaker of Helmholtz graduate school GEOSIM, 2011-2017
- Member of senate commission of for CRC program DFG, since 2016
- since 2004 Speaker of Helmholtz programme 'Geosystem: The changing Earth' at GFZ Potsdam
- Member of Think Tank of Helmholtz Association 2011-2014

AWARDS AND HONORS

1980 PhD fellowship by German Academic Scholarship Foundation
1987 Hermann Credner-Award of the German Geological Society
1998 Leibniz-Award, Deutsche Forschungsgemeinschaft (On 7/10))
1999 Member of the Berlin-Brandenburgische Akademy of Sciences, of Heidelberg Academy of Sciences (2001), and of Leopoldina Academy (2002)
2006 Elected member of Academia Europaea
2007-2008 Distinguished Moore Fellow at Caltech, Pasadena
2014-2015 Andrew Wiess Professor at RICE University, Houston
2015 G. Steinmann medal of German Geological Society

SUGGESTED READINGS (WEB RESOURSES OR SCIENTIFIC JOURNAL PAPERS)

To be found at: https://www.gfz-potsdam.de/en/staff/onno-oncken/sec40/

# PLATE TECTONICS: A GEOLOGICAL PERSPECTIVE

**Onno Oncken**
GFZ Potsdam, Germany

In the 1960s, the idea of plate tectonics began its triumphal advance in the Earth sciences. Fifty years earlier, polar explorer Alfred Wegener had developed his theory of *continental drift*. This first modern concept for the functioning of our planet was primarily based on two observations: the geometric fit of the continents in the southern hemisphere and the geographical distribution of past climate traces and fossils. However, Wegener's concept lacked a plausible mechanism to drive the drift of the continents. The subsequent revolution in the 1960s, leading up to the theory of *plate tectonics*, was inspired by observations resulting from technological developments – and from research driven by military objectives. To improve the navigation and location of submarines in World War II, the Allies had started to extensively explore topography and magnetism of the seafloor. The most spectacular result was the discovery of the Earth-spanning system of mid-ocean ridges, which, like the ocean floor with its equally discovered magnetic pattern, generally proved to be of magmatic origin. Almost at the same time, Kiyoo Wadati and Hugo Benioff discovered that earthquakes were concentrating where deep-sea trenches occur at the borders between oceans and continents on planes that dip obliquely beneath the continents. Again, these investigations originally had a military purpose: Globally distributed seismological stations were used for the monitoring of nuclear tests.

From these and other observations grew a completely new model of planet Earth. Accordingly, fresh basaltic magma continually penetrates the oceanic ridge, pushing the flanks apart and crystallizing. The newly formed crust drifts towards the continents and dives under these into the Earth's mantle. The most important finding against Wegener's continental drift was the insight that the entire solid shell of the Earth – now called lithosphere – is fragmented into several rigid plates that float on the so-called asthenosphere, a viscously deforming weak part of the upper mantle. By the 1970s, it was possible to explain all other key features of the earth - in particular the formation of mountains and sedimentary basins, the evolution and alteration of rocks, and the distribution of earthquakes, volcanoes, and mineral as well as fossil fuel resources - using plate tectonic theory. This fundamentally new paradigm revolutionized our view of planet Earth into one of a constantly changing system of moving plates on a convecting mantle. Since then we have learned that the coupled plate tectonic-surface-climate system is in fact essential for the habitability of our planet: plate tectonics, driven by the internal forces of Earth, forms mountains that provide the reactive land surface the erosion and weathering of which balances volcanic $CO_2$ emissions – thus stabilizing Earth's climate over Earth's long history. This feedback provides the fundamental conditions for protracted biological evolution and ultimately our human existence. The implications for society are twofold: Earth's resources enrich our life by technological advance – and hazards from geological processes threaten it.

This becomes particularly clear at the plate boundaries of our planet. They concentrate more than 90% of Earth's energy release through earthquakes and volcanoes, but also concentrate most of our resources – and host most of our rapidly growing megacities. Hence, understanding the Earth system is a first-order requirement. Recent research progressively reveals the intricate complexity in the functioning of Earth: Multiple feedbacks exist between the deep inner forces and geodynamic processes that shape the Earth and its changing habitats through geological time. These interactions occur at time scales of a few decades to many millions of years. Examples of the links and controls of deep Earth processes shaping life over long-term evolution include the oxygenation of our planet's atmosphere by photosynthetic microbes that became possible only by removing vast amounts of iron into Earth's core, or biological evolution by forming habitats for life. At slightly shorter time scales, we are beginning to appreciate the feedbacks between moving plates, and the deformation of their margins. Here mountain belts such as the Andes or the Himalayas rise and form topographic barriers to atmospheric circulation, thereby controlling their own erosional conditions and eventually impacting the mechanical conditions for their formation through 'lubrication' of plate interfaces with their detritus – or the lack thereof. At even shorter time scales, it is the competition between erosion-driven landscape rejuvenation, forced by uplift, and water flow in the weathering zone, forced by climate, that determines conversion of rock into soil and, as a result, the withdrawal of atmospheric $CO_2$ by weathering. Yet, while these relationships are increasingly recognized, the laws governing remain vague or unclear in many cases.

New technical developments currently help to pave the way towards conceptual advance. These, for example, include techniques such as seismic and space-borne observations of our planet; advanced simulations producing increasingly realistic and detailed models of the Earth system; new geochemical and isotopic tools, that allow us to determine the "rates and dates" of Earth processes; new technologies for rock and mineral analysis; and experimental investigation. Their application is resulting in new and unexpected discoveries. Examples include: the recent discovery of transient deformation – the so-called family of 'slow earthquakes' that went unnoticed before their discovery through the GPS technology –; the discovery that the entire crust of our planet is in failure equilibrium – or so close that minor perturbations such as wells or reservoir construction may trigger events –; the detection of very long-lived shear-wave velocity anomalies at the boundary between the Earth's core and mantle controlling the mantle dynamics and, in turn, the plate tectonic response at the Earth's surface; the recent detection of gravity transients preceding large subduction earthquakes; and the discovery that rock fracturing from these internal forces is setting the way soil is formed and eroded all challenge our current understanding.

The fact that new observations from new technologies are either unforeseen by our standard concepts or even defy prediction requires new avenues of research and conceptual advance. These not only include experimental and analytical research on deep Earth properties across all scales and their evolution through geological time but also the advancement in data science approaches. The growing awareness that processes driving the Earth System are virtually all intricately coupled exhibiting characteristic properties of complex systems, such as self-organized criticality, chaotic response patterns, nonlinearity and emergence, calls for a new strategy in Earth System Science. Complex systems science has been developed in Physics and Chemistry since the 1950s but has as yet found little uptake in the Earth Science Community. Benefitting from the advance in neighboring sciences will be instrumental in achieving conceptual advance towards a system sciences perspective in the Earth Sciences. New discoveries and breakthroughs in this exciting field will follow new technological developments, use of large interconnected data and an integrated system science approach. And – all of this requires appropriate education of the next generation.

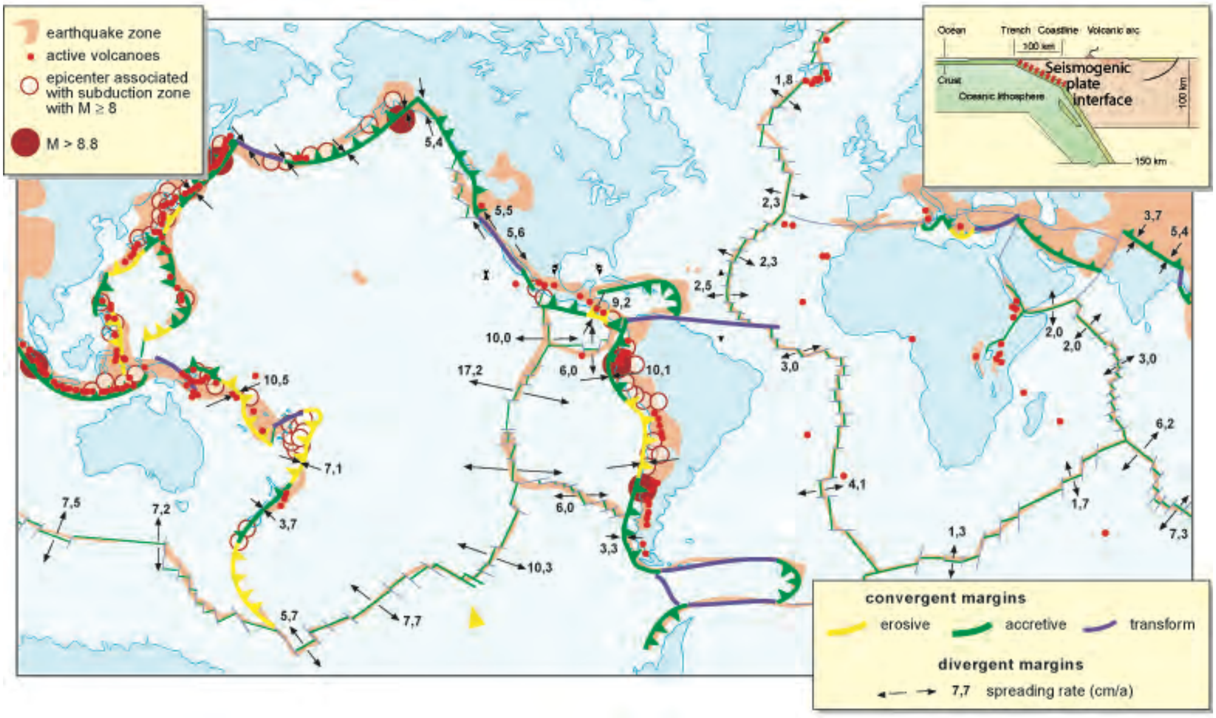


Fig. 1: The outer shell of Earth is divided into a dozen rigid plates, the most important of which are shown here. Where they collide, one dives beneath the other (subduction, indicated by lines with triangles). Here it can scrape off material from the upper plate (subduction erosion, yellow) or accrete material to it (accretion, green). At plate boundaries earthquakes and volcanism are strongly concentrated.

**Jean-Philippe Avouac**
California Institute of Technology
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http://web.gps.caltech.edu/~avouac/

**Education**

| | |
|---|---|
| 1987 | Ingénieur, Ecole Polytechnique, France |
| 1991 | PhD, (advisor: Paul Tapponnier), Institut de Physique du Globe de Paris, France |
| 1992 | Habilitation à diriger des recherches Institut de Physique du Globe de Paris, France |

**Career**

| | |
|---|---|
| 2018-present: | Director of the NSF/IUCRC center for Geomechanics and the Mitigation of Geohazards, California Institute of Technology |
| 2015- present: | Earle C. Anthony Professor of Geology, Professor of Mechanical and Civil Engineering California Institute of Technology |
| 2014-2015: | BP-McKenzie Professor of Earth Sciences, University of Cambridge |
| 2012-2014: | Earle C. Anthony Professor of Geology, GPS Division, California Institute of Technology |
| 2004-2014: | Director of the Caltech Tectonics Observatory |
| 2003-2012: | Professor of Geology, GPS Division, California Institute of Technology |
| 1996-2002: | Chef du Laboratoire de Télédétection et Risque Sismique, DASE, CEA, France |
| 1991-1996.1 | Ingénieur, Laboratoire de Géophysique, CEA, France |

**Research interests**

Jean-Philippe Avouac studies earthquakes and tectonic processes, in particular mountain building processes. His group has contributed to method developments in remote sensing, geodesy, geomorphology and seismology. He uses these techniques to inform theory, and develop models of earthquakes and deformation of the crust. His recent research has focused on the interplay between fluid flow and faulting, with the aim of advancing the understanding of the effect of fluid injection or withdrawal on subsurface deformation and seismicity.

**Publications and Services**

President-elect of the Tectonophysics section, American Geophysical Union; co-editor–in-chief, *Earth and Planetary Sciences Letters* (2018-present); co-editor-in-chief, *Tectonophysics,* (2014-2018); >180 publications in international peer reviewed journals; 2 patents in image processing.
Avouac Google scholar profile

**Awards and Honors**

Editors' Citation for Excellence in Refereeing for *Geophysical Research Letters* (2015)
Wolfson Merit Award of the Royal Society, UK (2014)
Elected Fellow of the American Geophysical Union (2014)
*Earth and Planetary Science Letters* Editorial Excellence Recognition Award (2013)
Alexander von Humboldt Foundation Senior Scientist Award (2010)
Editors' Citation for Excellence in Refereeing for *J. of Geophys. Res.* -Solid Earth (2008)'
Birch Lecture, American Geophysical Union (2007)
Editors' Citation for Excellence in Refereeing for *J. of Geophys. Res* -Solid Earth (2007)
Geol. Soc. of America Best Paper Award (2003)
E. A. Flinn Award of the International Lithosphere Program (1993)

# PLATE TECTONICS AND EARTHQUAKES

**Jean-Philippe Avouac**
California Institute of Technology, Pasadena, CA USA

The study of earthquakes has played a major role in the establishment of plate tectonics and the theory indeed provides a solid framework that explains to first order their distribution and characteristics, such as the type of faulting. Earthquakes delineate plate boundaries and contribute to accommodating relative plate motion. Early on, this rationale was the basis for hope that plate tectonics would provide a firm foundation for seismic hazard assessment, and eventually earthquake prediction. Fifty years after the plate tectonic revolution, assessing seismic hazard remains a major challenge though. We are still short of solid methods to estimate reliably the probability of occurrence, possible location and magnitude of the most extreme events. We have however made substantial progress on these questions in particular thanks to the possibility of using space geodetic techniques and remote sensing in addition to seismological monitoring of observed earthquakes and to monitor plate boundaries. With these techniques we can now measure the process of strain accumulation and release by earthquakes, the so called 'earthquake cycle'. I will discuss such observation and how they can be used to identify zones of seismic hazard and quantify the hazard. I will focus in particular on the Himalaya, which is a prime location to study the dynamics and seismicity at converging plate boundaries. I will review our current understanding of crustal deformation in the Himalaya and show that earthquakes are integral part of the mountain building process, and that Mw>8.5 earthquakes with a millenary return period are likely required. I will describe details of the 2015 Mw 7.8 Gorkha earthquake, Nepal and discuss what we learned from that particular event that can help assess the impact of future earthquakes in the Himalaya or at other plate boundaries.

*For a broader audience:*
*http://www.tectonics.caltech.edu/outreach/highlights/earthquakes_and_mountains_International_Innovation.pdf*

**Bárbara Ferreira**
Media and Communications Manager
European Geosciences Union
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Bárbara Ferreira, a Portuguese citizen, started working at the EGU Executive Office in Munich, Germany, as EGU Media and Communications Officer in September 2011, being promoted to EGU Media and Communications Manager two years later. She manages communications at EGU, including coordinating media-related and science communications between the Union and its membership, the working media, and the public at large. Her activities include producing EGU news items, press releases and the EGU newsletter, as well as managing the press office at the EGU General Assembly and coordinating all press activities at the conference. She also works on Planet Press, an EGU educational project that brings geoscience news to children, parents and teachers.

When not working for the EGU, Bárbara is a science writer specializing in astrophysics and space sciences, producing articles for the European Space Agency and others on a freelance basis. Before joining EGU, Bárbara worked as a public outreach assistant at the European Southern Observatory. Prior to that, she was an assistant scientific adviser (on secondment from her PhD) at the Parliamentary Office of Science and Technology in London.

Bárbara's background is in physics, mathematics and astronomy. She completed an undergraduate degree in astronomy from the University of Porto, Portugal, in 2005, and a master in applied mathematics (Part III of the Mathematical Tripos) from the University of Cambridge, UK, in 2006. She has a PhD in mathematical astrophysics, also from the University of Cambridge. Her thesis, completed and defended in 2010, focused on the variability of black-hole accretion discs.

## ABOUT PLANET PRESS

Planet Press (http://www.egu.eu/education/planet-press/) is an EGU educational project that aims to get children (mainly 7–13 year olds), as well as their parents and educators, interested in and engaged with up-to-date scientific research and news.

Planet Press articles are short versions of EGU press releases written in child-friendly language. Because EGU press releases cover research published in the various EGU scientific journals, Planet Press focuses on topics as varied as air pollution, glaciers, climate change, earthquakes, ocean sciences, droughts and floods, or space sciences. The texts are reviewed by both scientists and educators to make sure they are accurate and clear to their target audience. By sharing new and exciting geoscientific research with young kids, we hope to inspire them to develop an interest in the Earth, planetary and space sciences.

**Giuliana D'Addezio**
Istituto Nazionale di Geofisica e Vulcanologia
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Tel. +39 3405397277

Geologist, researcher at INGV in Active Tectonics and Paleoseismology, particularly for the characterization of seismogenic sources, the evaluation of seismic recurrence models and seismic hazard assessment in Italy and in the Mediterranean area. She has acquired Masters in "Advanced Studies in Museum Education" and since 2008, as coordinator of the INGV Laboratorio di Divulgazione Scientifica e Attività Museali, organize training and scientific dissemination activities through programs dedicated to schools, the organization and design of scientific exhibitions and contribution in national and international scientific events. She has been in charge for outreach tasks in national and European scientific projects and member of the Scientific Committee and the Organizing Committee of the IESO 2011 (International Olympics of Earth Sciences).
Since 2915, she is the Director of the Geophysical Museum of Rocca di Papa (Rome).

**Marina Locritani**
Affiliation: Istituto Nazionale di Geofisica e Vulcanologia
marina.locritani@ingv.it
Tel. +039 0187 794416

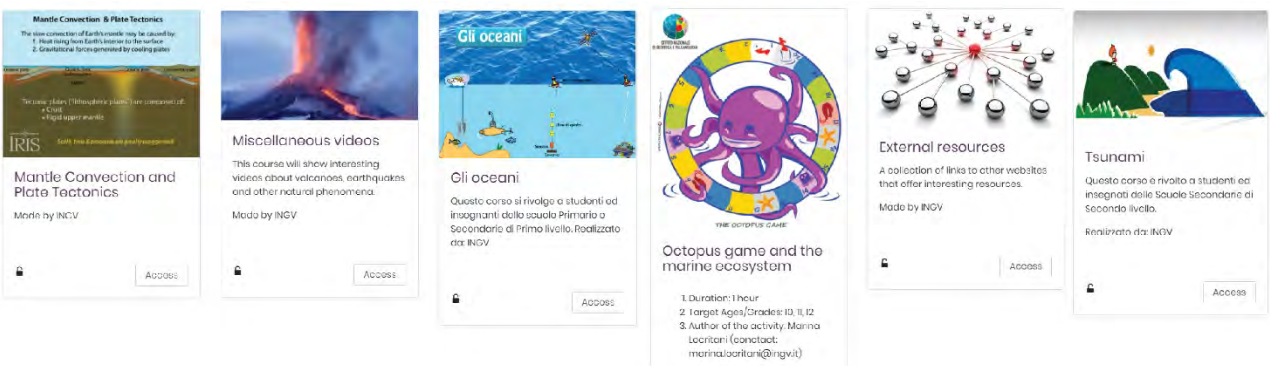
Researcher, PhD in Environmental Science – Marine Science
<u>RESEARCH INTERESTS</u>
Marine litter problem and physical oceanography
Outreach and citizen science activity

*SUGGESTED READINGS (WEB RESOURSES OR SCIENTIFIC JOURNAL PAPERS)*
ENVRI deliverable: http://www.envriplus.eu/deliverables/
Inj detail: D15.6 – Training for Teachers (http://www.envriplus.eu/wp-content/uploads/2015/08/D15.6-Training-for-Teachers.pdf)
ENVRI publication and conference proceeding: http://www.envriplus.eu/publications/
Ocean literacy for all: a toolkit: https://unesdoc.unesco.org/ark:/48223/pf0000260721

# ENVRIPLUS E-LEARNING PLATFORM

**Giuliana D'Addezio and Marina Longhitani**
INGV, Rome, Italy

ENVRIplus is an European Horizon 2020 project, that brings together research infrastructures, projects, networks and specialized technical partners to create an interdisciplinary and interoperable cluster across Europe. The project arises from the need of the scientific community to establish collaborations through the many traditional research fields to face the major challenges that society will have in the future, such as climate change, extreme events becoming increasingly frequent, and loss of biodiversity.
The ENVRIplus scientific community aims to increase awareness in students and in citizens on the great challenges that our planet is facing, bringing them closer to the research, and to disseminate knowledge on environmental topics.
We present the results of the *Work Package 15 – Training course for teachers*. The purpose is to favor teacher training and consequently students training on selected scientific themes faced within the ENVRIplus Research Infrastructures. In particular, the platform addresses major thematic research areas and challenges on Biodiversity and Ecosystem Services, Greenhouse effect and Earth Warming, Ocean acidifications and Environmental sustainability.
The e-Learning Platform is included in e-Training ENVRIplus Platform (https://training.envri.eu/) that is devoted to providing professional courses for the project partners. The e-Training Platform, also, incorporated a Scientific Gaming section (http://scientificgame.envri.eu/). The e-Learning Platform section is addressed to students and teachers and its aim is to offer a point of reference to the school community (elementary, middle and high) on the recent environmental themes, providing: courses, links to the other European and worldwide platforms, and illustrated boards to aid teachers to develop innovative lessons.



**Jean-Luc BERENGUER**
Science teacher International HighSchool
Valbonne Sophia Antipolis, France
EGU Committee on Education
berenguer@unice.fr

**Education and research**

Education & Outreach team at GEOAZUR Research laboratory
Project leader for:
EDUMED Observatory project (University Côte d'Azur)
http://edumed.unice.fr
INSIGHT Education (Geoazur CNRS, OCA)
http://insight.oca.eu
EGU Committee on Education member & IGEO Senior Officer
Education & Outreach Officer for IODP 345 expedition: Hess Deep Plutonic Crust - https://iodp.tamu.edu/scienceops/expeditions/hess_deep.html

**Publications and Services**

- Jean-Luc Berenguer, Françoise Courboulex, Audrey Tocheport, and Marie-Paule Bouin, Tuned in to the Earth from the school, EduSismo: the French educational seismological network - Bulletin de la Societe Geologique de France, January/February 2013, v. 184, p. 183-187, doi:10.2113/gssgfbull.184.1-2.183
- Jean-Luc Berenguer, Hubert Ferry, Franck Pascucci, le cahier du SISMO, CRDP 2006
- Florence Bigot-Cormier, Jean-Luc Berenguer, how students can experience sciences and become researchers : tracking MERMAID floats in the oceans, SRL, Volume 88, Number 2A March/April 2017, doi: 10.1785/0220160121

# EXPLORE PLATES TECTONIC MODEL WITH DATA AND MAPS

**(hands-on activity)**

**Jean-Luc BERENGUER**

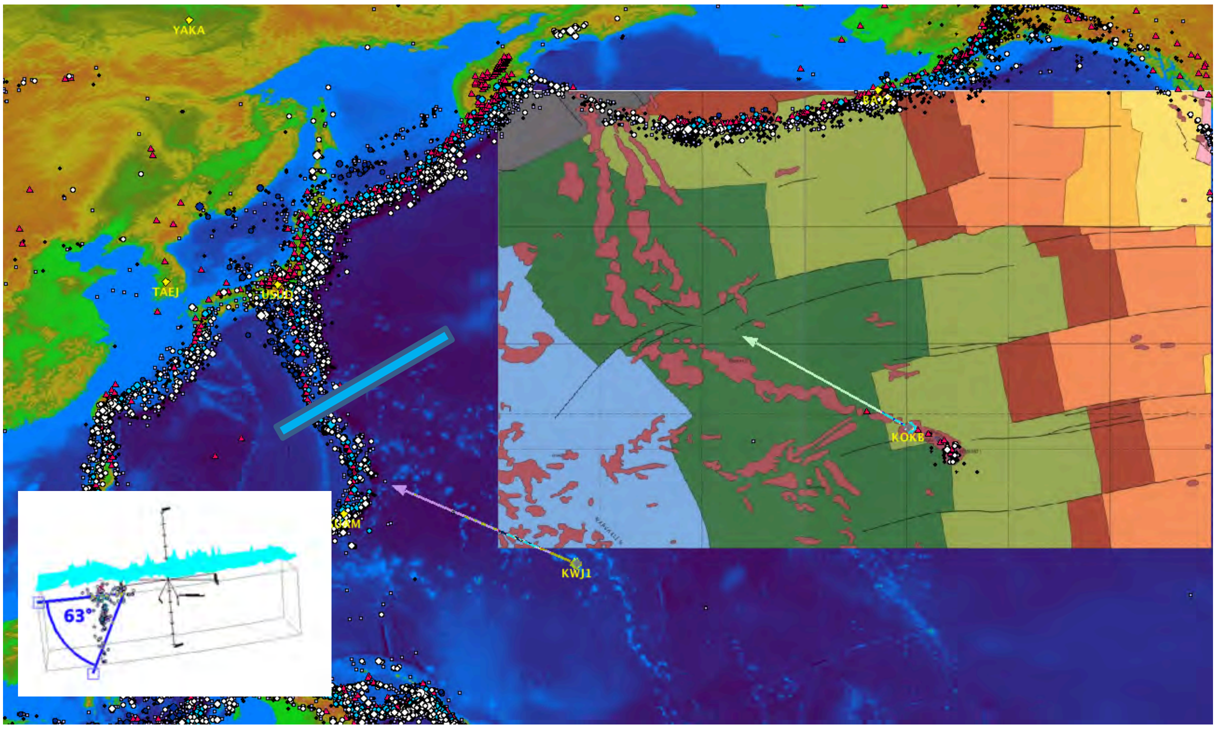
EGU Committee on Education

Hands-on session will present some practical activities to propose to your students using maps and data to understand the Earth.

The hands-on session suggests exploring the world geologic map from the perspective angle of the plate tectonics model.
A first exploration of the oceans geology will show the relative youth of the crust, and a symmetry of the sedimentary deposits along the ridges.

The comparison of the age of the continental and the oceanic crusts will underline the importance of subduction zones in the genesis of the continental lithosphere. Once the plates boundaries are identified, the study of GPS time series of GPS will allow us to refine deformation and the mobility of tectonic plates.

Then, the digital tools (data base, geology mapping, Geographic Information System) can be used as a complement to study the relative speed of lithospheric plates and/or the drawing of 3D cross section for lithosphere and/or the overlapping of the seismic tomography.



**Chris King**
Emeritus Professor of Earth Science Education
Keele University, Keele, UK
chris@earthlearningidea.com

**Education**

1971 BSc Honours in Geology, 2(2); University of Bristol.
1977 MSc 'Sedimentology', (Distinction); University of Reading.
1978 Postgraduate Certificate in Education (Geology, Chemistry, Geography); University of Keele.

**Career**

| | |
|---|---|
| Oct 1971 - July 1976 | De Beers Consolidated Mines Ltd., Kimberley, South Africa. |
| Sept 1978 - July 1996 | School teacher, Altrincham Grammar School for Boys |
| Sept 1996 – Aug 2002 | Science Education Lecturer: Earth sciences, Keele University |
| Sept 2002 – Aug 2006 | Senior Lecturer in Science Education: Earth sciences |
| Sept 2006 – Dec 2015 | Professor of Earth Science Education |
| Jan 2016 – today | Emeritus Professor of Earth Science Education |
| Sept 1999 – Dec 2015 | Director of the Earth Science Education Unit at Keele University |

**Membership of learned bodies and professional associations**

Chair of the European Geosciences Union (EGU) Committee on Education (CoE); Chair of the International Union of Geological Sciences (IUGS) Commission on Geoscience Education (COGE); Adviser (past-Chair and instigator) of the Council of the International Geoscience Education Organisation (IGEO); Chair of the Earth Science Education Forum (England and Wales) (ESEF (E & W); Past-Chair of the Earth Science Teachers' Association (ESTA) and current Chair of the ESTA Secondary Committee; Chair of Examiners and moderator for the Welsh Joint Education Committee (WJEC/Eduqas) Geology 'A' level Examination Committee; Fellow of the Geological Society.

**Research interests and other career details**

- the development of Earth science teaching nationally and internationally
- monitoring a national programme of Earth science professional development
- misconceptions in Earth science understanding
- leading of the Earthlearningidea team, publishing Earth science activities for the Earthlearningidea website (more than 300 activities so far).
- providing educational consultancy to the 'Building Earth Science Education Resilience' project

**Awards and Honours**

- 2003 – winner of the Geological Society's 'Distinguished Service Award'
- 2012 – winner of the Geologists' Association's 'Halstead Medal'

**Suggested readings (chapters in books)**

King, C. (2017) *Fostering deep understanding through the use of geoscience investigations, models and thought experiments – the Earth Science Education Unit and Earthlearningidea experiences*. In Vasconcelos, C. (Ed) *Geoscience education: indoor and outdoor*, 3-23, Switzerland: Springer.
King, C. (2013) *A review of the Earth science content of Science Textbooks in England and Wales*. In Myint Swe Khine *(ed) Critical Analysis of Science Textbooks: evaluating instructional effectiveness*, 123-160. Dordrecht: Springer.
King, C. (2013). *Using Research to Promote Action in Earth Science: Professional Development for Teachers.* In, Vincent Tong (ed) *Geoscience Research and Education*. 311-334. Dordrecht: Springer.

# THE STRUCTURE OF THE EARTH AND PLATE TECTONICS

**(hands-on activity)**

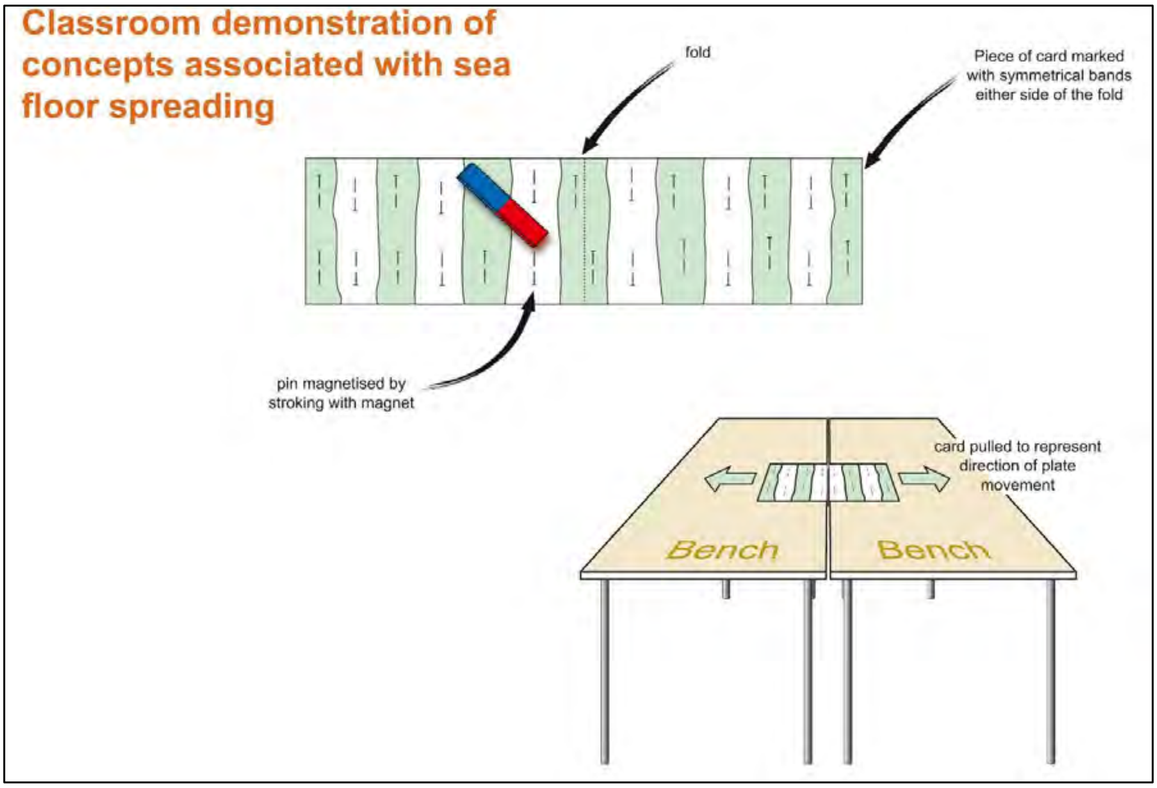
**Chris King**

EGU Committee on Education

'The structure of the Earth and Plate Tectonics' workshop gets to grips with the wide-ranging evidence for the theory that underpins our detailed modern understanding of our dynamic planet – the theory of **Plate Tectonics**. The workshop progresses through a series of hands on interactive activities that are designed to help students develop their understanding. It uses several independent sources of evidence supporting the theory, including using rock and fossil evidence, seismic records, geothermal patterns, geomagnetism, and large-scale topographical features, both above and below sea-level. The workshop provides a reconstruction of plate movements over the past 450 million years which explains the record contained in the rocks beneath our feet - recording amazing plate journeys across the face of our planet.

The workshop and its activities provide the following outcomes:

- an introduction to plate tectonics;
- distinction between the 'facts' of plate tectonics and the evidence used to support plate tectonic theory;
- a survey of some of the evidence supporting plate tectonic theory;
- an introduction to the evidence for the structure of the Earth and the links between the structure of the outer Earth and plate tectonics;
- explanation of some of the hazards caused by plate tectonic processes;
- methods of teaching the abstract concepts of plate tectonics, using a wide range of teaching approaches, including practical, hands on, interactive and electronic simulations;
- approaches to activities designed to develop the thinking and investigational skills of students.




**Dr. Christophe Vigny**
Laboratoire de Géologie at Ecole Normale Supérieure / CNRS, Paris, France
vigny@geologie.ens.fr
Tel : + 33 1 44 32 22 14


**Education / Diplomas**

| | |
|---|---|
| 1975-1982 | **Lycée International de Saint-Germain-en-Laye, Portuguese section**<br>"Baccalauréat série C" Math-Physics, with honors |
| 1982-1987 | **University Paris XI Orsay**<br>DEUG A (Math/Physic)<br>Licence of physics – option astronomy<br>Master of physics - option fluid mechanics |
| 1987-1989 | **University Paris XI - ORSAY / ENS Ulm**<br>Ph.D. in Earth Sciences entitled "Geoïd and internal dynamics of the Earth" (Dir. Y. Ricard, (Jury C. Froidevaux, J. Woodhouse, Y. Ricard, J.-P. Montagner, M. Rabinowicz, C. Sotin). |
| 2006 | **University Paris VII**<br>H.D.R. entitled "GPS: from plate tectonics to seismology" (Jury: P.Tapponnier, R.Madariaga, Y.Gaudemer, E.Calais,P.Huchon, P.Briole, B.Ambrosius) |

**Career**

| | |
|---|---|
| 1989-1990 | **ONERA,** DMPH (P. Touboul)<br>Post. Doc.: modeling of space gravimetric measurements: ARISTOTELES/GRADIO satellite project. Research made in the frame of my active military service |
| 1990-1991 | **MIT** (Boston, MA, USA), EAPS (B. Hager)<br>Post. Doc.: Spatial Geodesy (GPS) and plate tectonics |
| 1991- → | **CNRS,** "Laboratoire de Géologie" at ENS, Paris, France<br>**Full time researcher:** Measurement of the Earth crustal deformation associated to active faults with high seismic hazard. |

**Research interests**

I use modern style space geodesy (GPS) to quantify plate tectonics and deformation around active faults. For this purpose, I install arrays of permanent (cGPS) stations and networks of geodetic benchmarks which I survey regularly to monitor their positions. These measurements allow to quantify the crustal deformation before, during and after an earthquake. My goal is to understand how tectonic plates move and deform, how major earthquake nucleate and rupture. I apply these methods on different faults around the world where seismic hazard is high: South-East Asia (Indonesia – Sumatra and Sulawesi, Malaysia, Thailand, Myanmar), Chile (from Patagonia to Atacama), Iran (Zagros, Alborz), Nepal (Himalayas), Djibouti (East African Rift), etc...

**Publications and Services**

*http://www.geologie.ens.fr/~vigny*

## PLATE TECTONICS:
## THE ORIGIN OF EARTHQUAKES IN AND AROUND STABLE PLATES

**Christophe Vigny**
Laboratoire de Géologie at Ecole Normale Supérieure / CNRS, Paris, France

It has been over 50 years now, and following the discovery of plate tectonics, that Earth scientists have been able to describe inter-plate earthquakes as a consequence of plate-tectonics. Indeed, most earthquakes occur along plate boundaries. Their occurrence corresponds to the sudden release of the stress generated by the strain that have been slowly accumulated there because of friction along the faults marking plate boundaries. Because plate motion is steady (over the time scale relevant for earthquakes: thousands of years - not millions), accumulation of deformation never stops and resumes immediately after an earthquake. The succession of long periods of steady accumulation (hundreds to thousands of years) and sudden rupture (seconds or minutes) is known as the seismic cycle. This simple concept has been very efficient at identifying hazardous areas (places where deformation is accumulated) and understanding recurrence patterns. Over the last decades, great efforts have been made to further quantify seismic hazards. They have been partly successful. Thanks to decisive progress in space Geodesy (mostly GPS & INSAR), Seismology and Tectonics, we now know how to determine if a given fault area has developed the necessary conditions for the occurrence of a near-future earthquake. In many places, we know how much deformation is being accumulated, where exactly and since when. This information has allowed us to make significant progresses towards the assessment of seismic hazards along active faults. However, at least two major issues remain and challenge our understanding of the seismic cycle and our capacity to mitigate seismic hazards.

First, we still don't know exactly when an earthquake will happen. The adjective "near-future" often remains extremely fuzzy. We also don't clearly understand why and how an expected event of anticipated size would sometimes simply not occur (be delayed) or would deviate from expectations and become an extreme event of unexpected magnitude. This is why B. Gutenberg's statement still holds: "*This laboratory does not predict earthquakes. Specific predictions giving time and place come from amateurs, publicity-seekers, believers in the occult, or just plain fools*" (*letter from B. Gutenberg, dir. of Caltech seismological lab. Sept. 1947*). The recent giant earthquakes that occurred on subduction zones during the first decade of the 21$^{st}$ century (Sumatra 2004, Mw 9.2; Chili 2010, Mw 8.8;

Japan 2011, Mw 9.0) show that if the occurrence of an earthquake in those places was predictable, the giant event that actually occurred there was not expected. The reasons why a “standard” moderate or large earthquake would evolve into a much larger giant earthquake (Mw > 8.5) remain elusive. We don’t know if an initiating rupture “knows” from the very beginning that it will become a giant rupture or if on the contrary this happens only by chance and after one or several bifurcation(s) at key moment(s) where favourable conditions have developed. Earthquakes often come as a surprise, giant ones particularly, and we always learn from their specific occurrence. Presently, progress is being made: Modern seismology and space geodesy (GPS), provide important constraints on this theme, helping to quantify deformation before the earthquake and identify key moments in the rupture process and the physical conditions that prevailed then and there.

Second, intra plate seismicity remains a puzzling feature. Following plate tectonics theory, plate interior do not deform, hence the very sparse intra-plate seismicity. However, earthquakes do occur once in a while inside plates, and sometimes quite large ones. However, we detect no accumulation of deformation there before the earthquakes occur, so the reason for their occurrence is totally unclear. We don't know if these earthquakes obey the general pattern of the seismic cycle (accumulation-release), but with such extremely low rate that they are well below the detection level of our tools. In this case, the theory is correct and the framework of the seismic cycle is adequate to quantify intra-plate-seismic hazard. It is only a technical challenge to be able to measure extremely small deformation accurately enough and extract the tectonic load from the noise associated to many other processes. We don't know if fossil stress can be stored in the earth crust for extremely long periods and released by earthquakes long after the process at the origin of the stress building has stopped. In this case, an earthquake could occur anywhere (everywhere stress has been stored in the past) and any-time (as soon as the impeachment mechanism is waved and/or something triggers the release). In this case, the challenge is to identify places that are currently under stress, but where strain is “frozen”, quantify the stress (with which tools?) and identify triggering mechanisms, including human activity.
Example of both inter-plate and intra-plate seismicity and earthquakes will be shown along with a discussion of their plausible mechanisms and their consequences.

**Mathilde Cannat**
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## Education
1990. Habilitation à Diriger des Recherches, University of West Brittany, Brest.
1983. PhD University of Nantes, France.

## Career
2001. senior CNRS researcher, Institut de Physique du Globe, Paris.
1996. senior CNRS researcher, University of Paris VI.
1986. junior CNRS researcher, University of West Brittany, Brest.
1984-1986. Post-doctoral scholar, Durham University, UK.

## Research interests
Structure of the oceanic lithosphere; tectonic, magmatic and hydrothermal processes at mid-ocean ridges; slow-spreading ridges; exhumation and serpentinization of mantle rocks in extensional domains.

## Publications and selected services
139 papers. Google Scholar as of july 2018: total citations 7450, h-index 49.
*http://www.researcherid.com/rid/F-9304-2010*

- (2018-). Chair of the Science Service Group, European Research Infrastructure EMSO (European Multidisciplinary Seafloor and water column Observatory).
- (2015- ). Member of the Scientific Committee of the City of Paris.
- (2013- ). Member of the Board, IPGP doctoral school.
- (2009- ). Chair of the Technical and Scientific Committee for the EMSO-France Research Infrastructure. This is the french component of the EMSO European Multidisciplinary Seafloor and water column Observatory. We operate from as a CNRS-Ifremer consortium and coordinate french-led activities at 3 EMSO observatory sites (Lucky Strike on the Mid-Atlantic Ridge, Ligurian sea, Marmara Sea). We also assist the Ministry of Research's representatives to the EMSO board.
- (2009-2014). Member of the International Ocean Drilling program Board of Governors.
- (2008-2013). Head of the Géosciences Marines team of IPGP : 38 researchers, engineers, post-docs and students.

## Suggested readings (web resources or scientific journal papers)
Cannat, M., 1993, Emplacement of mantle rocks in the seafloor at mid-ocean ridges: Journal of Geophysical Research Solid Earth, v. 98, no. B3.

Cannat, M., Sauter, D., Mendel, V., Ruellan, E., Okino, K., Escartin, J., Combier, V., and Baala, M., 2006, Modes of seafloor generation at a melt-poor ultraslow-spreading ridge: GEOLOGY, v. 34, no. 7, p. 605.

Sauter, D., Cannat, M., Rouméjon, S., Andréani, M., Birot, D., Bronner, A., Brunelli, D., Carlut, J., Delacour, A., Guyader, V., MacLeod, C.J., Manatschal, G., Mendel, V., Ménez, B., et al., 2013, Continuous exhumation of mantle-derived rocks at the Southwest Indian Ridge for 11 million years: Nature Geoscience, v. 6, no. 4, p. 314–320, doi: 10.1038/ngeo1771.

**OVERVIEW ON SEAFLOOR SPREADING**

**Mathilde Cannat**
CNRS-Institut de Physique du Globe de Paris, France

Plate tectonics continuously moves and renews the surface of our planet, causing mountains to grow, older oceanic plates to sink into the Earth's interior, and new oceanic plates to be formed at mid-ocean ridges, a process called seafloor spreading. Seafloor spreading occurs at a specific type of plate boundary, called the mid-ocean ridges, where new oceanic plates are formed and diverge at velocities between 20, and less than 1 cm/year. Mid-ocean ridges extend over more than 60 000 km on the surface of the Planet. They are active volcanic chains, but also domains of faulting, particularly when the divergence is slow (<4 cm/yr). Normal faults there accommodate a good part of the plate divergence, interacting with magmatism to shape the new oceanic plates, and bringing rocks up from the Earth's mantle to the seafloor. The third tool mid-ocean ridges have to do their job is hydrothermalism: seawater gets into the highly fractured new plates and reacts with the rocks. The rocks are modified in the process, heat and chemical elements are extracted and transferred to the Ocean, and the hydrothermal fluids feed original microbial communities. Seafloor spreading thus has a large impact not only on the composition of the oceanic plates, but also on chemical exchanges between the solid Earth and the Ocean, and on the diversity of seafloor biology. This presentation will attempt to give you an overview of what we know of magmatism, faults, and hydrothermal circulation at mid-ocean ridges and also outline several open questions for future research.

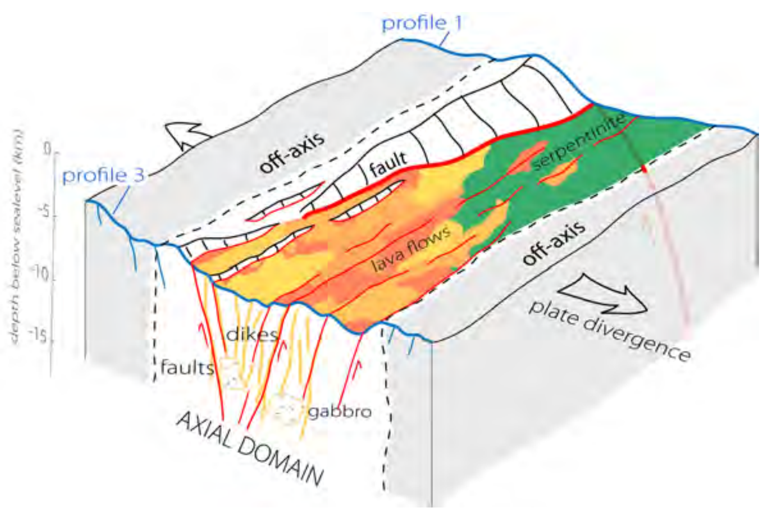


*Figure : Conceptual sketch of a very slow spreading ridge (Cannat et al., 2017). The two plates diverge and new seafloor is created in the axial domain (ie: the mid-ocean ridge). Depending on magma supply, faults take up a variable proportion of the plate divergence. Large offsets along faults cause material from the upper mantle to be lifted up to the seafloor and be hydrothermally altered into a rock called serpentinite (in green). In more magmatic areas, the new seafloor is made of lava flows (in yellow to red).*

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www.geosita.com (in Italian)

**Education**

2001 University Federico II of Naples (Italy) BSc (First Class Honors Degree) Geological Science; 2006 University Federico II of Naples (Italy) PhD in Earth Science Thesis Title: "The fluidization phenomena into the pyroclastic density currents dynamics"; 2013 University Luigi Vanvitelli BSc (First Class Honors Degree) Environmental Science.

**Career**

Lecturer in "Environmental Geology" and "Geomorphology and Physical Geography" at Guglielmo Marconi University; Teacher of Math and Science at IC Vanvitelli (Caserta), Italian Public Junior High School.

**Research interests**

Natural Hazards risk perception; Engaging students/teachers in STEM.

**Publications**

Gravina T., Greco R., Boccardi V., Cossu C., Piccioni E. And S. Occhipinti (2018) Could participation in a Science Olympiad engage students in studying Earth Science? The results from the participant in Italian Earth Science Olympiad. Terræ Didatica (in press).
Gravina T. Occhipinti S., Boccardi V., Fantini F. 2018.The Italian Earth's Science Olympiad: a reflection on results of first edition. Rend. Soc. Geol. It. 45:23-30
Gravina, T., Muselli, M., Ligrone, R., and Rutigliano, F. A.: SUstaiNability: a science communication website on environmental research, Natural Hazards Earth System Science, 17, 1437-1446, https://doi.org/10.5194/nhess-17-1437-2017, 2017.
Gravina, T., Figliozzi, E., Mari, N. F . De Luca Tupputi Schinosa Landslide risk perception in Frosinone (Lazio, Central Italy) Landslides (2016). doi:10.1007/s10346-016-0787-2
Bareschino P., Gravina T., Lirer L., Petrosino P., Marzocchella A. Salatino P., (2007). Fluidization and de-aeration of pyroclastic mixtures: The influence of fines content, polydispersity and shear flow. Journal of Volcanology and Geothermal Research 164, 284-292.
Bareschino P., Marzocchella A. Salatino P., Gravina T., Lirer L., Petrosino P. (2006). Self-Fluidization of fastly moving gravity currents with implication on pyroclastic flow. Fluidization XII New Horizons in Fluidization Engineering, May 13-17, 2007 (Canada).
Gravina T., Lirer L., Marzocchella A., Petrosino P., Salatino P., (2004) "Fluidization And Attrition Of Pyroclastic Granular Solids". Journal of Volcanology and Geothermal Research 138, 27-42.

# SCIENTIX AND EUROPEANA: ONLINE RESOURCES TO TEACH EARTH SCIENCES

**Teresita Gravina**
EGU Committee on Education

Teaching today is a multifaceted profession and is considerably different from what it used to be. According to the *Council Recommendation on Key Competences for Lifelong Learning* (2018), to support the development of key competences it is important to pay special attention to some particular developmental points one is: "fostering the acquisition of competences in sciences, technology, engineering and mathematics (STEM), taking into account their link to the arts, creativity and innovation and motivating more young people, especially girls and young women, to engage in STEM careers".

To reach this goal it is important for teachers to be up-to-date with STEM and have access to a wide repository of material that could be used during lessons. Two European Projects, Scientix and Europeana are providing interesting teaching material and professional development opportunity for teachers to support the development of students' key competencies in STEAM (Sciences, Technology, Engineering, Art and Mathematics).

Europeana is a digital platform for cultural heritage that gives access to over 53 million items including image, text, sound, video and 3D material from the collections of over 3 500 libraries, archives, museums, galleries and audio-visual collections across Europe. Europeana Collections provides access to digitized items with sophisticated search and filter tools to help you find what you're looking for. The dedicated thematic collections cover a wide range of topics like science, art, fashion, music, photography. They provide multiple perspectives on historical, political, economic, cultural and human developments across Europe and beyond and are perfect to enrich educational resources as well as inspire learners with Europe's digital cultural heritage. The Europeana Digital Service Infrastructure (DSI) showcases and provides online access to Europe's cultural and scientific heritage. Currently, the Europeana DSI project is in its 4$^{th}$ consecutive year. The Europeana DSI-4 project continues the work of the previous three Europeana Digital Service Infrastructures (DSIs). It is the fourth iteration with a proven record of accomplishment in creating access, interoperability, visibility and use of European cultural heritage in the five target markets outlined: European Citizens, Education, Research, Creative Industries and Cultural Heritage Institutions. The previous stage, the Europeana DSI-3 project involved a Developer Group of teachers from European countries who produced datasets, pedagogical scenarios and learning activities using the Europeana Collections, as well as open source, professional development materials for teachers.

Scientix is a project funded by the Horizon 2020 program of the European Union for research and innovation, that promotes and supports an Europe-wide collaboration among STEM (Science, Technology, Engineering and Maths) teachers, education researchers, policy makers and other STEM education professionals. Scientix is coordinated by European Schoolnet (EUN), a Brussels-based not-for-profit organization, led by 34 ministries of education. EUN is a driving factor for innovation in teaching and learning and fosters pan-European collaboration between schools and teachers. The Scientix project supports teachers in their professional development with face to face workshops, Moodle courses and webinars, and provides a repository of teaching materials, developed by different European projects on STEM topics.

**Barbara ROMANOWICZ**
Collège de France, Paris and University of California, Berkeley
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**Education**

1970-74: Ecole Normale Supérieure, "Sèvres", Paris, France; 1972: Maîtrise de Mathématiques Pures, Université Paris 6.; 1973: Agrégation de Mathématiques, Paris, France; 1975: Master of Science in Applied Physics, Harvard University; 1975: Doctorat de 3e cycle in Astronomy, Université Paris 6.; 1979: Doctorat d'Etat, Université Paris 7, Spécialité Géophysique.

**Career**

2016-pres: Professor of the Graduate School, University of California, Berkeley; 2011-pres: Physics of the Earth's interior chair, Collège de France, Paris; 1991-2016:Prof. of Geophysics, University of California at Berkeley; 1991-2011 Director, Berkeley Seismological Laboratory (http://www.seismo.berkeley.edu); 1986-90: Directeur de Recherches, C.N.R.S., I. P. G., Paris, Director, Geoscope Program; 1981-86: Chargée de Recherches, C.N.R.S., I. P. G., Paris., Director, Geoscope Program; 1979-81 Post Doctoral Associate, M.I.T., Cambridge, Mass.; 1978-79: Attachée de Recherches, C.N.R.S., Institut de Physique du Globe, Paris.

**Research interests**

My primary research interest has been the development of new tomographic methodologies to improve resolution in the imaging of deep earth structure using seismic waves, with application at the global and continental scale, with the goal of improving our understanding of the internal circulation that drives plate tectonics on our planet. I have also worked on earthquake source problems. In addition to contributing to the development of data collection infrastructure in geophysics, including global and regional networks of sensors and associated open archives, I have been advocating for the geophysical instrumentation of the ocean floor, a necessary component for improving illumination of the earth's interior. I also have an interest in planetary science. Four of my former PhD students (2 in France and 2 in the US) are currently involved in the InSight mission which recently successfully landed on the planet Mars.

**Publications**

Over 240 publications in peer reviewed journals. Most relevant recent publications:

French, S. W. and B. Romanowicz (2015) Broad plumes Rooted At The Base Of The Earth's Mantle Beneath Major Hotspots, *Nature*, 525, 95-99.

Romanowicz, B. (2003) Global mantle tomography: progress status in the last 10 years, *Annu. Rev. Geoph. Space Phys, 31 (1)*, 303.

**Awards and honors (a selection)**

1990 Fellow, American Geophysical Union (AGU); 1992 Silver Medal of the Centre National de la Recherche Scientifique (French NSF); 1999 A. Wegener Medal of the European Union of Geosciences; 2001 Fellow, American Academy of Arts and Sciences; 2003 Gutenberg Medal, European Geophysical Society; 2005 Member, US National Academy of Sciences; 2008 Chevalier de la Légion d'Honneur, France; 2009 Inge Lehmann Medal, AGU; 2011 Harry Reid Medal of the Seismological Society of America; 2013 Member, Académie des Sciences, France; 2018 Foreign Member, Polish Academy of Sciences.

# IMAGING THE DEEP EARTH

**Barbara Romanowicz**
Collège de France, Paris and University of California at Berkeley, USA

Earthquakes, tsunamis, volcanic eruptions: all are dramatic consequences of plate tectonics on Earth with important societal impact. They remind us of the powerful internal forces that drive the motions of tectonic plates at the surface of the earth. In order to understand flow patterns in the earth's mantle, seismic imaging, which uses seismic waves generated by natural earthquakes to illuminate the earth's internal structure, is an ever improving tool for mapping regions where slow upwelling and downwelling flow is occurring at the present time. I will briefly describe the principles of seismic tomography, the challenges related to the sparse coverage of the earth's surface dictated by the available distribution of earthquake sources and of land masses and how we can compensate for this using seismic waves that bounce around the mantle. I will illustrate how this has been facilitated in recent years by access to high performance computing and how the progressively sharper global scale images of key features of our planet's interior, including "slabs" and "plumes", inform our thinking about present day mantle dynamics and its evolution through geologic time.

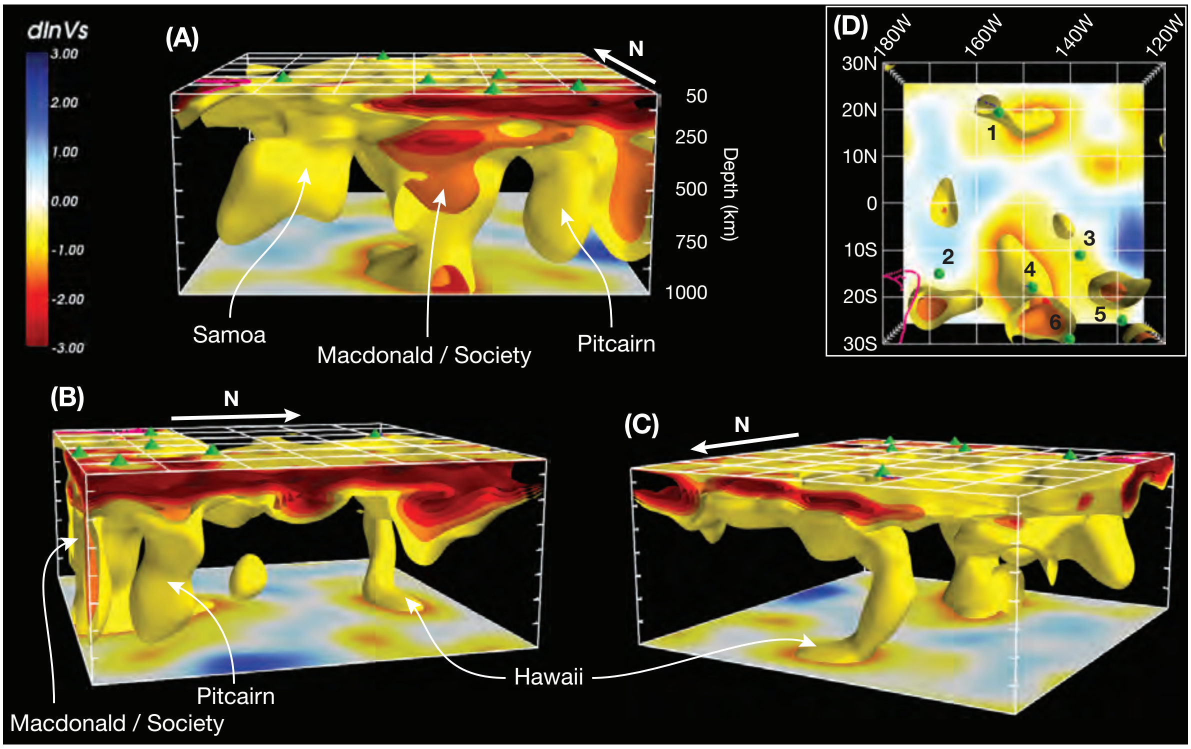


*Figure: The "plumbing system" beneath the south-central Pacific ocean as revealed by seismic tomography. Yellow and red colors represent regions of hotter than average material. (A), (B),(C) 3D rendering viewed from respectively south, east and southwest. (D) View from the top, only structure deeper than 400 km is shown. Green cones represent "hotspot" volcanoes at the surface of the earth. Most of these hotspots plot close to the surface expression of tube-like "plume" structures that bring hot material up from the deep mantle.*


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Centre for Earth Evolution and Dynamics
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**Education**

| | | |
|---|---|---|
| PhD in Geophysics | Massachusetts Institute of Technology | 1994-2000 |
| BA in Physics and Geophysics | University of California at Berkeley | 1990-1994 |

**Career**

| | | |
|---|---|---|
| Earth Modeling Team Leader | Centre for Earth Evolution & Dynamics | 2016-now |
| Professor of Mantle Dynamics | University of Oslo, Dept. of Geosciences | 2016-now |
| Assistant & Associate Professor | University of Hawaii at Mānoa | 2008-2016 |
| Assistant Professor | Johns Hopkins University | 2005-2008 |
| Postdoctoral Scholar | University of Michigan | 2001-2005 |
| Research Scientist | Mission Research Corporation | 2001 |
| Postdoctoral Scholar | California Institute of Technology | 2000-2001 |

**Research interests**

- Deep mantle flow, and its link to topography and plate tectonics on Earth
- Subduction, mountain-building, and other tectonic processes
- Sea level change on timescales ranging from decades to millions of years
- Seamounts and intraplate volcanism
- Patterns of earthquake seismicity on Earth
- Convection within rocky planets
- Dynamics of exoplanets

**Publications and services**

- 70 peer-reviewed publications, including several recent high-profile articles:
- Dangendorf, S., M. Marcos, G. Wöppelmann, **C.P. Conrad**, T. Frederikse, and R. Riva (2017), Reassessment of 20th century global mean sea level rise, *Proceedings of the National Academy of Sciences, 114*, 5946-5951, doi:10.1073/pnas.161007114.
- **Conrad, C.P.** (2013), The solid earth's influence on sea level, *Geological Society of America Bulletin, 125*, 1027-1052, doi:10.1130/B30764.1.
- **Conrad, C.P.**, B. Steinberger, and T.H. Torsvik (2013), Stability of active mantle upwelling revealed by net characteristics of plate tectonics, *Nature, 498*, 479-482, doi:10.1038/nature12203.

**Awards and honors**

CAREER Award from the National Science Foundation (2012)

**Suggested readings (web resourses or scientific journal papers)**

- **Conrad, C. P.** (2017), How good were the old forecasts of sea level rise?, in *EGU Geodynamics Blog,* edited by G. Shephard, http://blogs.egu.eu/divisions/gd/2017/09/13/modern-day-sea-level-rise/.
- Sames, B., M. Wagreich, and **C.P. Conrad** (2016), Why do Cretaceous sea-level changes matter in today's global change discussions?, *IGCP 609 Popular Scientific Overview,* http://www.univie.ac.at/igcp609/index-Dateien/page0010.html.
- **Conrad, C. P.** (2015), Plate Tectonics, in *Discoveries in Modern Science: Exploration, Invention, Technology*, edited by J. Trefil, pp. 870-880, Macmillan Reference USA, Farmington Hills, MI.

# PLATE TECTONICS:
# LINKING SURFACE GEOLOGY TO EARTH'S DEEP INTERIOR

**Clinton P. Conrad**
Centre for Earth Evolution and Dynamics, University of Oslo, Norway

Plate tectonics is a scientific theory that provides a unifying understanding of links between Earth's internal dynamics and geologic change on the Earth's surface. In this theory, the Earth is covered by about 15 rigid tectonic "plates" that move across the Earth's surface at speeds of a few centimeters per year (Figure 1). Plate tectonics has been shown to explain a variety of geological observations, such as the locations of volcanoes and earthquakes, the topography of the seafloor, and the formation of Earth's mountain ranges. Ultimately, however, plate tectonics is a manifestation of convection within Earth's interior: it is the primary mechanism by which our planet cools. As a result, the driving forces for plate tectonics ultimately arise from deep within Earth's interior, and thus geologic change at the surface can be seen as the product of our planet's active interior dynamics.

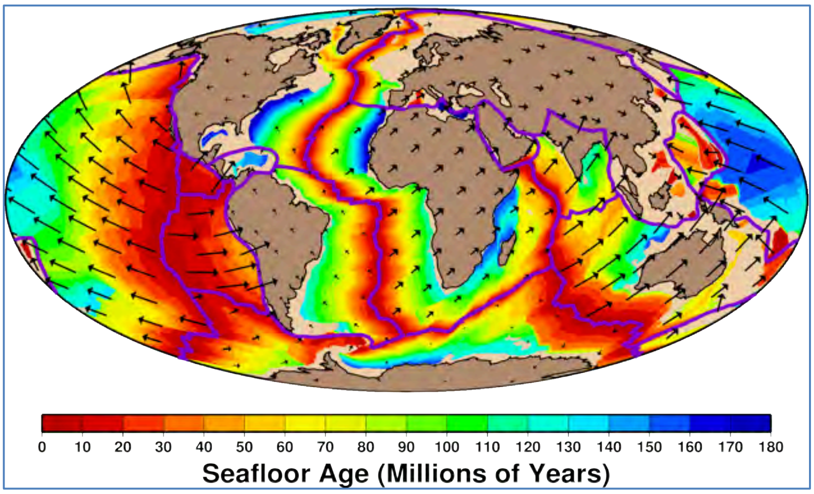


***Figure 1.*** *The tectonic plates typically move away from mid-ocean ridges and toward subduction zones (plate boundaries here are shown by purple lines). This causes seafloor ages to increase moving away from the mid-ocean ridges (colors). Plate speeds range from 5-10 cm/yr in the Pacific basin to 1-3 cm/yr in the Atlantic basin (black arrows). Plate motions are the surface expression of large-scale deformation within Earth's interior.*

In the past two decades, greatly improved images of Earth's interior structures, combined with rapid advances in computer technology, have allowed us to develop sophisticated computer models of Earth's interior dynamics. These models show that the Earth's mantle, which is the 3000 km thick rocky layer between Earth's crustal rocks and its metallic core, is undergoing slow and constant deformation as hotter rocks rise to the surface and colder rocks sink deeply. These dynamics produce a broad pattern of mantle flow that includes broad up-wellings and down-wellings that stretch laterally across continents and ocean basins. The tectonic plate motions are merely the surface expression of this flow.

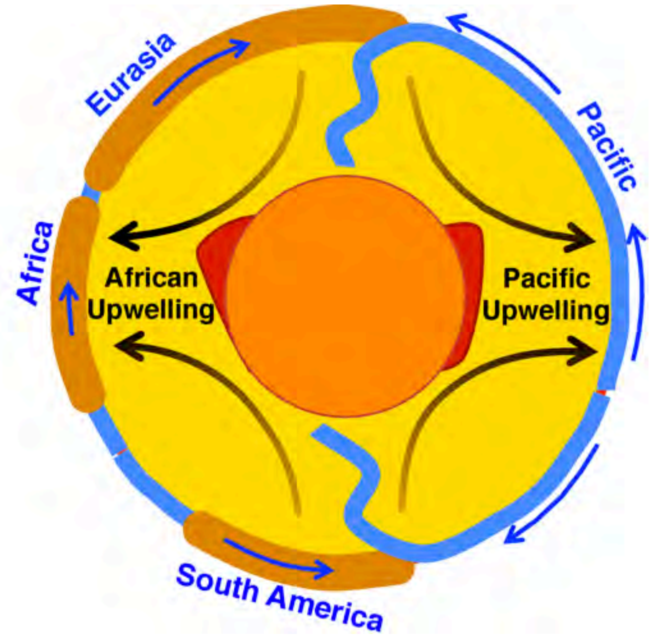


*Figure 2. Cartoon diagram showing the general pattern of mantle flow for a cross-section of Earth cut approximately through the equator, looking toward the North Pole. The flow is dominated by two major upwellings, one beneath the Pacific and another beneath Africa, with major downwellings between them. We expect that this general pattern of plate motions has remained relatively steady through time, although the positions of the plates on the surface have changed.*

Recently, we have been able to use computer models of mantle flow to understand the patterns of mantle flow that are active within Earth's interior today, and how they have changed in the recent past. These models link the dynamics of Earth's deep interior with its surface geology, and help to explain a variety of geological observations. In this talk, I will describe these models, and discuss the pattern of mantle flow that we think is operative for the present-day. This pattern includes two broad upwellings beneath Africa and the Pacific that are surrounded by a ring of downwellings that surround the Pacific basin. This pattern of flow (Figure 2), which we think has remained in operation during Earth's recent history, helps to explain a variety of geologic observations including the broad high topography of Africa, and the ongoing uplift of mountain ranges such as Tibet and the Andes. Plate tectonic processes also explain flooding of continental regions worldwide by sea level about 100 million years ago (during the age of dinosaurs), and the drop of sea level since then.

Finally, I will discuss how understanding the link between plate tectonics and the deep mantle is important for helping us to understand the processes that led to the formation and breakup of the supercontinent Pangea. Although Pangea was one of the first tectonic features to be attributed to plate tectonic movements, the mantle forces that led to its assembly and breakup have remained enigmatic. Using models that link mantle flow to plate motions, we can now begin to understand the Pangea within the context of deep mantle flow patterns. Indeed, mantle flow occurring deep within the Earth provides us with a framework for understanding plate tectonic movements on Earth's surface, both today and within Earth's geologic past.

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**Education**

B.Sc. Carnegie-Mellon University, 1973, Chemistry
B.A. Carnegie-Mellon University, 1973, Psychology
M.S. The University of Maine at Orono, 1976, Oceanography (Chemical)
Ph.D. The University of Texas at Austin, 1981, Chemistry (Geochemistry)

**Career**

| | |
|---|---|
| 1993 - present | Professor, Dept. Environnental Sciences, Univ. Virginia |
| 2008 - 2009 | Program Director, NSF, Geobiology and Low Temperature Geochemistry. |
| 2004 - 2006 | Visiting Scholar, Smithsonian Institution, Washington, DC. |
| 1989 - 1993 | Assoc. Prof., Dept. Environmental Sciences Univ. Virginia |
| 1990 | Investigator, Geophysical Lab, Carnegie Institution Washington, DC |
| 1989 - 1990 | Guest Researcher, GEOTOP, Univ. Quebec, Montreal, Quebec CA |
| 1987 - 1990 | Associate Prof., Dept. Earth Sciences, Memorial Univ. St. John's, NF |
| 1983 - 1987 | Asst. Prof., Dept. Earth Sciences, Memorial Univ. St. John's, NF |

**Research interests**

Special emphasis on fossil materials, fossil fuel origin and migration, early diagenesis of organic matter, abyssal ocean cycling of carbon and nitrogen, abiotic synthesis of organic materials and organic pollutants. Molecular approaches to isotope analysis. Isotope studies of food webs in modern and fossil ecosystems. Resolution of diet in early humans.

**Publications**

Macko, S.A. (2016) Environmental Aspects of Hydrocarbon Exploration in the Arctic. In: Challenges of the Changing Arctic: Continental Shelf, Navigation and Fisheries M. H. Nordquist, J. N. Moore, and R. Long, Editors. Brill Academic Pub. The Netherlands pp 130-144.

Ward, J.W., Warden, J.M., Bandy, A.M., Fryar, A.E., Brion, G.M., Macko, S.A., Romanek, C.S. and Coyne, M.S. (2016). Use of nitrogen-15-enriched Escherichia coli as a bacterial tracer in karst aquifers. Groundwater: 54:830-859.

MacAvoy, S.E., Cortese, N., Cybulski, J., Hohn, A. and Macko, S.A. (in press) Using multiple tissue types and stable isotopes to assess origins among stranded Western Atlantic dolphin (Tursiops truncatus) in North Carolina. Mar. Mammal Sci.

**Awards and Honors**

Fellow, Geochemical Society (2004)
Fellow European Association of Geochemistry (2004)
Faculty Teaching Award, University of Virginia (2007)
State of Virginia Faculty Award (2008)
President's Medal, Memorial University (1987).

**Suggested readings**

*https://en.wikipedia.org/wiki/Geomagnetic_reversal*
*https://en.wikipedia.org/wiki/Plate_tectonics*

# DEMONSTRATING THE LINKAGE OF SEA FLOOR SPREADING TO PALEOMAGNETISM/ MAGNETIC REVERSALS IN SUPPORT OF THE THEORY OF PLATE TECTONICS

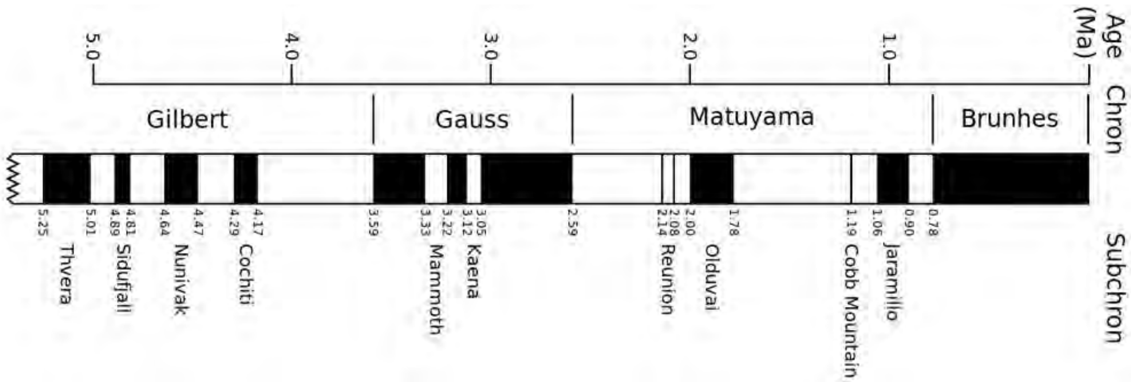
**(hands-on activity)**

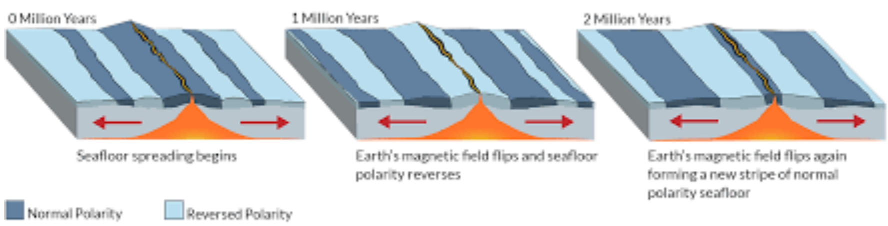
**Stephen Macko**

Department of Environmental Sciences, University of Virginia, Charlottesville, USA

Committee on Education EGU

While recognition of the need for explain surface Earth phenomena was clearly needed, that unified concept was only a fairly recent event in the proposal of the Theory of Plate Tectonics. Singular observations were widespread. The shapes of the continents appeared to fit together like the pieces of a long-disassembled puzzle. Crustal temperatures, using heat probes showed higher heat anomalies along the Mid-Ocean Ridge and diminished values more distant and as one approached the trenches. The oldest ocean sediments were only 200 million years in age, and those were found on the edges of the ocean basins, great distances from the Ridge. The edge of the Pacific Ocean was a literal "Ring of Fire" being marked by numerous volcanoes, and heightened earthquake activities, with epicenters having increasing depth below adjacent landmasses. There was incredible similarity in rock ages and fossils (Paleozoic fern seeds of *Glossopteris* and reptile mesosaurs) contained in corresponding bands on opposite sides of the Atlantic Ocean (between West Africa and the eastern coast of South America). Warm water coral reef fossils were discovered in cooler, high latitude locations, whereas glacial deposits were discovered in more tropical locations. Perhaps the most persuasive evidence in support of a theory for plate tectonics came from the observations in the magnetic orientation of surface rocks and the polar reversals they recorded. The changes in Earth's magnetic field is recorded in rocks around the globe. Paleomagnetic studies of the ocean floor showed similarity in timing changes in polarity of the magnetic poles. This exercise attempts to show how such a correlation could be envisioned using spreading of oceanic crust and magnetic polar reversals. While a mechanism for plate motion still remained to be postulated, magnetic stratigraphy led to powerful support for the theory of plate tectonics.

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## Education

| | |
|---|---|
| 1992 | HDR (Habilitation to be PhD advisor), Paris-SUD-XI University, France |
| 1987 | PhD Department of Physics, Paris-SUD-XI University, France |
| 1983 | Master of Sciences in Solid, Atomic and Nuclear Physics, University of Caen, France |

## Career

My career in climate began in 1992 when I shifted from accelerator physics to climate physics (from Maxwell to Navier-Stokes equations). I first studied paleoclimate modelling and was involved in a first PMIP (Paleoclimate Modelling Intercomparison Project).
I became the head of the Modelling group 1998-2005 (20 persons) and then the Head of paleoclimate division at LSCE (100 persons, including data and modelling) from 2006-2010. Afterwords, I was the head of multidisciplinary group at LSCE which was mostly scientific animation.
Amongst other responsibilities I was the head of a Research Training Network (2007-2010) on climate cryosphere interaction and also the head of CNRS multidisciplinary program on paleoclimate (Eclipse 2000-2007). Head of two ANR national program and many bilateral PHC project (Norway, Japan and China).
Advisor of 19 PhD.

## Research interests

My main interest is climate modelling. I studied many time periods from Snowball Earth to Quaternary and even 21$^{st}$ century climate changes. The methodology I use is to quantify past scenarios of climate change and to explore their causes using appropriate climate models. For instance, cryosphere carbon and climate models for Snowball Earth (1,2), tectonic and climate for Cenozoic (3, 4), orbital forcing carbon and climate models for Quaternary (5) and cryosphere and climate models for 21$^{st}$ century (6).

## Publications and Services


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3. Zhang, Z, G Ramstein, M Schuster, C Li, C Contoux, Q Yan, Aridification of Sahara caused by Tethys Sea shrinkage during Late Miocene, Nature, 513, 401-404, 2014.
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# PLATE TECTONICS AND CLIMATE

**Gilles Ramstein**
CEA-LSCE, Gif-Sur-Yvette, France

One century ago many forcing factors of the climate system were already identified. On the one hand Alfred Wegener published his important book "Die Entstehung der Kontinente und Ozeane" on plate motion and associated with Wladimir Peter Koppen, they depicted the effect of this latitudinal shift on climate and vegetation; one the other hand M. Milankovitch understood the high frequency forcing associated to orbital variations, tectonics and astronomical imprints on climate variations at geological time of millions and thousands of years respectively. An important effect was however missing: the link between tectonics, carbon cycle and climate. Feedback and regulation of the Earth system will be revealed long after by James Walker.

In this lesson, we will explain the intricate relationships of this tryptic and go through the exospheric carbon cycle. As a second step, we will give illustrations of climate changes driven by tectonics through variation of atmospheric carbon content. We will first use the most striking feature depicting failure in this regulation: the Neoproterozoic glaciation of the Earth (717-635 Ma), when the break-up of the Rodinia supercontinent led to a tectonic configuration that optimized the $pCO_2$ decrease. As a third step, we will illustrate more recent episodes, from Eocene to present day of effect of tectonics on climate associated with the disappearance of a large epicontinental sea: the Para-Tethys and the major climate changes produced by the Tibetan Plateau and the African rift uplifts. These last examples show how tectonics shaped the climate of the Earth at different geological times.


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## Education

2004: Diploma in Civil Engineering Department University of Patras
2006: Master in Seismic design of structures in Civil Engineering Department University of Patras

## Career

2005-2006: Structural modelling and analysis of the lattice roof structure of the archaeological excavation in Akrotiri Santorini (In cooperation with the scientific committee appointed to investigate collapse mechanism) and evaluation of partial collapse mechanism upon dead loading.

2006-Present: Structural Designer for various Industrial and residential Buildings composing of different structural system (Steel/Concrete/Timber).

2008-Present: Monitoring engineer for Structural Dpt of Rion Antirrion Bridge, involved in the maintenance of Structural Health Monitoring system instrumentation, as well as with the data analysis and engineering interpretation of the records. Engaged with the structural design of Building and maintenance equipment for Rion Antirion Bridge.

## Research Interests

Structural modelling, analysis and design of structures, Earthquake structural design, Modal Identification, Ambient structural vibration. Modal Operational Analysis. Sensor technology. Data acquisition. Data analysis Technics.

## Publications and Services

Olivier Flamand, Fabrice De Oliveira, Aris Stathopoulos-Vlamis, Panagiotis Papanikolas, Akis Panagis, Using non continous records from full scale monitoring system for fatigue assessment, EWSHM2014, July 08-11, 2014, Nantes, France

Panayotis Papanikolas, Aris Stathopoulos-Vlamis, Akis Panagis, Alain Pecker, Samuele Infanti, The behavior of Rion-Antirion Bridge during the Earthquake of “ACHAIA-ILIA” on June 8, 2008, 3rd fib International Congress – 2010

# BRIDGING THE RIFT
# EARTHQUAKE DESIGN OF THE RION-ANTIRRION BRIDGE

**Akis Panagis**
Structural Department of Rion Antirrion Bridge, Patras, Greece

The Rion Antirrion Bridge is located over the strait between Peloponnese and mainland Greece, at the west end of the Corinth gulf. The surrounding environment presented exceptional combinations of harsh conditions such as significant water depth, weak sedimentary seabed, increased seismic risk, active tectonics and high corrosivity, that had to be quantified and addressed through the design process.

The Bridge structural consists of a continuous cable stayed composite deck of 2252 m, fully suspended over 4 piers that are simply resting on the reinforced sea bed through shallow foundations.

This presentation focuses on the methodologies and tools implemented during the design and the construction of the Bridge, to address the risk imposed by the combination of earthquakes and the current tectonic movements in relation with the other particularities of the area.

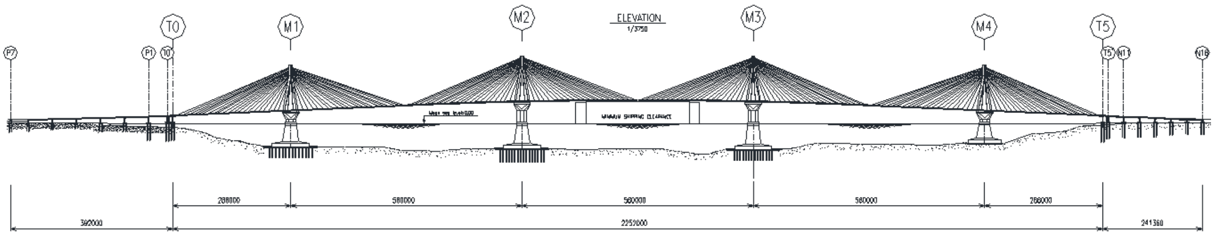
At first the general characteristics of the structure are mentioned, along with the design data input, i.e. seismic hazard analysis overview and strait opening rate.

Then, the principles of structural calculation and verifications of structural design focusing on both response spectra approach and acceleration time history analysis, always focusing on Bridge design are discussed.

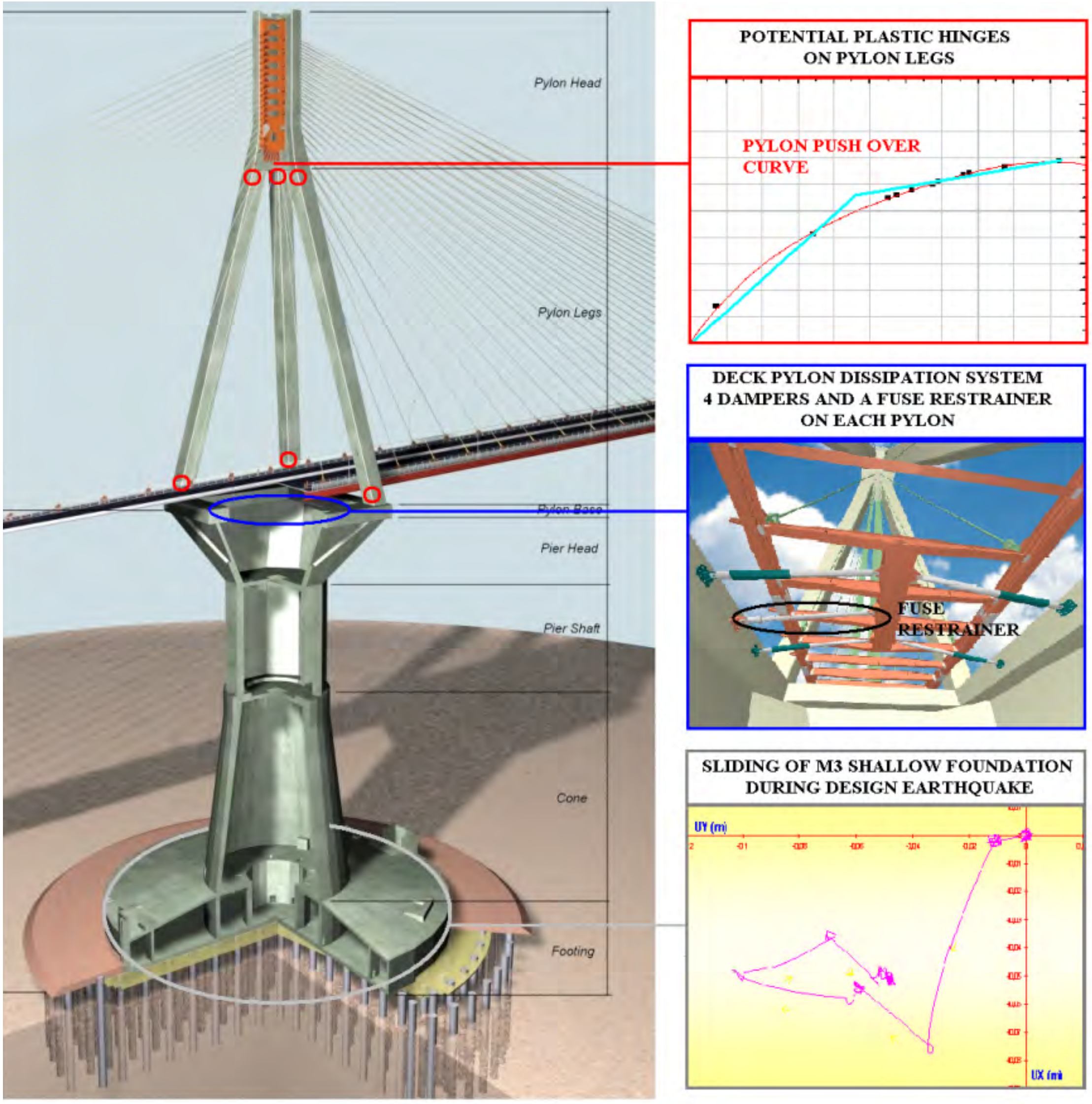
A significant part of the seismic design process is the notion of capacity design along with the envisioned energy dissipation mechanisms. For Rion Antirrion Bridge, the dissipation mechanism is unique (in size and capacity) involving active hydraulic dampers system installed at piers location, controlled damages on specially detailed concrete areas of pylon legs and sliding of the piers on sea bed.

Further, the features and equipment of the structure that allows safe operation without interruption and the integration of possible rift displacement that could occur between each pier in any direction (horizontal or vertical) are discussed.

Finally, a case study regarding the structural response of Rion-Antirrion Bridge during the ML 6.5 earthquake event of JUNE 8$^{th}$ 2008 is presented through the measurement recorded by a permanent monitoring system.




*Overview of the Rion Antirrion Bridge*




*Seismic energy dissipation mechanism of Rion-Antirrion Bridge*

**Dr. Francesco Sarti**
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and Training Activities
Directorate of Earth Observation Programmes
ESA/ESRIN
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**Education**
Master Degree in Electrical Engineering (University of Rome *La Sapienza*).
PhD on the subject of optical-radar remote sensing for the monitoring of surface deformation (University of Toulouse *Paul Sabatier*).

**Career**
After his Master Degree, he was hired in 1990 at the Operation
Center of the European Space Agency in Germany (ESA/ESOC) in the area of mission analysis and orbit control manoeuvre optimization. He then moved to precise orbit determination and to orbit and attitude control and continued his career at ESA/ESTEC in The Netherlands.

In 1997, he moved to CESBIO and then to CNES, Toulouse, where he worked for his PhD while working as a Project Manager for the *International Charter on Space and Major Disasters*, conducting R&D activities for remote sensing applications to disaster management and natural risk monitoring, interferometric monitoring of several seismic areas and providing training courses in Earth Observation.

After a short period at Italian Space Agency (2001) as a technical interface ASI-CNES for the cooperation COSMO-SkyMed / Pléiades, he joined ESA/ESRIN, in Italy, working in Earth Observation applications; since 2007, he coordinates the Education and Training Activities in Earth Observation.

# USE OF SPACE-BASED DATA FOR PLATE TECTONICS APPLICATIONS

**F. Sarti*, A. Mouratidis**, G. Pezzo*** and S. Salvi*****

* ESA (Italy), **Univ. of Thessaloniky (Greece), *** INGV (Italy)

The advent of Earth Observation (EO) from space, as well as airborne imagery, has provided new insights and tools for plate tectonics and in general, all Earth Sciences. These tools have allowed scientists to better understand and model the Earth's crust and to identify features related to processes at different scales affecting its structure. Until recently, systematic acquisitions from dedicated satellites have been lacking; nowadays, thanks to regular acquisitions and short revisit times, new satellite missions are enabling EO to become a fundamental tool, in complement to navigation (GNSS) and in-situ-measurements, to measure small-scale crustal deformation over large areas with high spatial resolution, contributing to improving our understanding and modelling of active tectonics (Ref. 2).

Geomorphological and topographical features like mountains, valleys and rifts, which shape the "face of the Earth", can be successfully observed and modelled (with an increasingly higher resolution) using optical and Synthetic Aperture Radar (SAR) imagery from space. Similarly, SAR and/or optical satellite data are powerful tools for surface and deep geological and tectonic structures detection, especially where seismic data are not available (Ref. 4). Stereo optical data and simultaneous radar acquisitions (e.g. SRTM and Tandem-X missions) have allowed the creation of finer and more precise Topographic Models (Digital Elevation Models) worldwide. Multispectral satellite data presently allow classifying land cover, whereas it is expected that the analysis and mapping of soil properties, including minerals, will soon benefit from forthcoming hyperspectral missions.

Several satellite-based systems and techniques such as Global Navigation Satellite Systems (GNSS) and SAR Interferometry (InSAR), allow to measure accurately ground displacements. Over many years, GNSS have provided useful and very precise (mm accuracy) displacement measurements over long and continuous periods, essential for geodesy applications and active tectonics studies. However, these systems provide punctual data, at location of GNSS stations, which also need being installed in the field and maintained/inspected regularly. Since 1991, however, with the launch of ERS-1, followed by ERS-2, the information provided by GNSS can be enriched and complemented with large scale ground displacement maps computed from InSAR. This technique, based on the difference of two non-simultaneous SAR phase images acquired from two satellite passes over (roughly) the same orbit, has allowed us to compute the maps of ground displacement (occurred in the time span between two acquisitions) over large regions with an accuracy of a few cm (or even a few mm, under certain conditions), (astonishingly) from a height of 800km. With new generation satellites, like Sentinel-1 (A and B), the revisit time, therefore the temporal frequency of observation (temporal resolution) has gone down from 35 days to 6 days, whereas the width of the images has increased from 100 to 250 km (S-1 IW mode, regularly used in acquisitions over land). The horizontal sampling of the measurement can be greatly reduced (metric or sub-metric level) using satellites like Radarsat-2, TSX or CSK. Moreover, nowadays the availability of various SAR missions with different radar bands (X, C, L, with radar signal wavelength around 3, 5.6 and 23 cm respectively) allows to select the sensitivity (scale) of the targeted displacement measurement (1/2 the wavelength) as well as the amount of measurement noise, that will eventually affect the accuracy of the displacement maps derived. Indeed displacement accuracy and noise depend on the sensor wavelength (roughly the longer the wavelength, the lower the accuracy and vice versa; and the opposite for the noise). Mapped displacement is along the Line of Sight (LoS) of the radar signal (Fig 1a) and mainly reveals the vertical component (uplift or subsidence). The use of two LoS measurements allows us to evaluate the horizontal (East-West) and vertical displacement components. Moreover, a smaller the displacement, the better the accuracy, and vice versa. For example, in the case of large earthquake, the accuracy of the observed displacement decreases approaching to the surface fault rupture, where the displacement is too large to be observed with this technique (appearance of phase difference noise, decrease of correlation). In these cases, near the fault, other techniques like SAR correlation or even optical correlation can be used, with the advantage that an information about the horizontal component of the ground displacement can be inferred, an important complimentary information to that obtained from InSAR (Fig.1a, Ref .5).

These techniques allow us to measure ground coseismic displacements, that can be synthetically reproduced using numerical models to identified geometrical and cinematic behaviours of the activated faults. Fault modelling allows scientists also to compute stress transfer onto surrounding faults, and/or to map new faults triggered by an earthquake, that were not previously known (Ref. 2). The accuracy of InSAR can be improved in the case of long temporal series of acquisitions (multitemporal InSAR); in this case, even very slow deformation rates in stable points over several years / decades can be measured. For example, these tecniques can be used to measure not only coseismic deformation but also slow intersesimic deformations (post-seismic, pre-seismic) of a few cm/year or mm/months typical of various (non-locked) faults[4], a useful information for applications in tectonic modelling, seismology and geophysics. Using multitemporal InSAR, scientists have been able to use ESA Envisat ASAR data to monitor the moving apart of the two tectonic plates in the East African Rift by detecting surface displacement with cm accuracy over several years, revealing that the dormant Mount Longonot in Kenya rose by 9 cm between 2004 and 2009. Tectonic activity such as the movement of magma underground may have caused this deformation of the surface above. In another case (Ref. 4), PS-InSAR stacking of Sentinel-1 dataset allowed the detection of fractures induced by neotectonics in Eastern Romania, characterized by the movement of blocks in opposite directions around 5-10 mm/year. Similar techniques (precise correlation of SAR images, as well as SAR coherency images) can also help detect a fault line that ruptured at depth (blind faults), which is not visible easily from ground observations (Fig. 1b and 1c), as not all ruptures reach the surface (Ref. 2 and Ref. 3, including a very interesting animation). All this different information can be assimilated into seismic and tectonic models (Fig.2), helping us to better understand the entire earthquake cycle and to estimate (the probability of) future hazards.

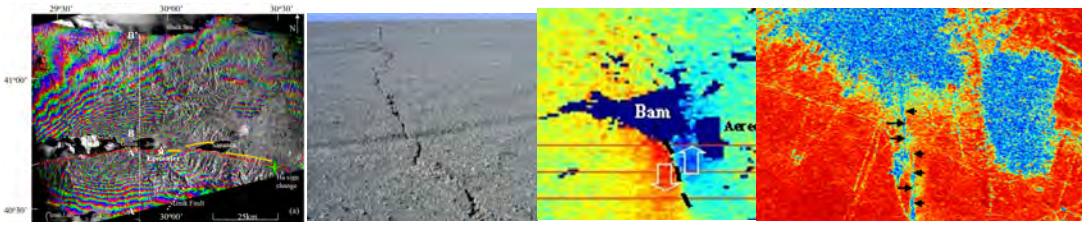


*Fig.1a (left): ERS-2 interferogram of the Izmit earthquake (1999): this allows to compute the co-seismic deformation map along the LoS of the radar signal. Fig.1b (second left): ground observation of the blind fault rupture (barely observable at the surface) southern of the city of Bam, following the Bam earthquake of 2003. Fig.1c, 1d (third and fourth left): the same fault rupture observed on an ASAR coherency image and on an azimuth shift map obtained by precise correlation of the ASAR pair (Ref. 5)*

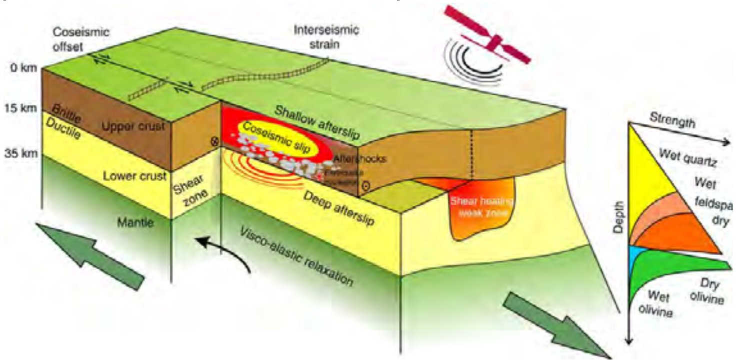


*Fig.2 Satellite geodesy offers the opportunity to measure the complete earthquake cycle: from slip in the upper crust, its relationship with aftershocks and fault segmentation; to post seismic deformation and interseismic strain accumulation across fault zones between earthquake (Ref. 2)*

Similar information about inflation and deflation of volcanoes can be obtained using the same technique. This information can be obviously related to phenomena taking place in the magmatic chambers of volcanoes and, together with a variety of different measurements and in-situ measurements, can help to improve volcanic models.

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4 *relative motion between plates has typical magnitude of tens of mm/year*

For this reason, the acquisition strategy of ESA SAR missions (presently, Sentinel -1) is such that frequent regular acquisitions over all major seismic and volcanic areas in the world are acquired, thus building up a huge archive of data complementing similar archives obtained by the previous SAR missions (ERS-1, ERS-2, ENVISAT ASAR). Examples of such regions are the whole Andean region, S. Andreas' fault in California, Israel, Japan, mount Etna, Campi Flegrei and Yellowstone (the so-called supervolcanoes) and many others. Volcanology and tectonics institutes worldwide (like e.g. IPGP in France, INGV in Italy and ISMOSAV in Greece) receive, process and constantly assimilate SAR data acquired over major active volcanoes and seismic areas (together with GNSS and many other data) into their models, aiming at improving the forecast of eruptions and the estimation of seismic hazards.

Although InSAR provides very useful information about tectonic phenomena at local, sometimes regional, scale, other space-based techniques, have been used to analyse plate motion at larger or even global scale. On top of the already mentioned Navigation techniques, Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) ought to be mentioned. In SLR a global network of observation stations measures the round trip time of ultrashort light pulses sent from ground to retroreflectors on board satellites. Range measurements of mm accuracy are then used to derive accurate measurement of orbits and, in turn, to obtain accurate measurements of the motion (mm/year) of stations. Measurement of motions on a global scale in a geocentric reference frame (Ref. 6). VLBI is a space-based technique used in geodesy, however it is not based on satellite data but rather on an array of radio telescopes: by means of simultaneous data collection from one single radio source via a worldwide array of radio telescopes, the relative time-of-arrival of signals from that source to each telescope can be very accurately determined. By observing many radio sources spread widely over the sky over long time periods, very precise measurements of the relative 3-dimensional position of globally distributed telescopes is possible with mm accuracy, thus allowing the measurement of motions of the Earth's tectonic plates (Ref. 7). Different results from all possible different techniques (VLBI, GNSS, DORIS and PRARE systems) are integrated within international network of space geodetic observatories (Ref. 8).

Finally, space-based measurements can also help to investigate paleo-geology, paleogeography and thus the paleohistory of our planet.

**References:**

(Ref. 1) Elliott, J. R., Walters, R.J., and Wright, T.J. (2016) "The role of space-based observation in understanding and responding to active tectonics and earthquakes", Nature Communications, doi: 10.1038/ncomms13844

(Ref. 2) https://comet.nerc.ac.uk/golden-age-tectonic-remote-sensing/

(Ref. 3) https://www.esa.int/Our_Activities/Observing_the_Earth/Highlights/Africa_s_ups_and_downs

(Ref. 4) https://peerj.com/preprints/27084.pdf

(Ref. 5) Sarti F. (2014), PhD thesis: "Potentiel de la télédétection optique-radar pour le suivi des changements et déformations de la surface terrestre : application à la gestion des risques naturels" http://www.theses.fr/2004TOU30289

(Ref. 6) https://ilrs.cddis.eosdis.nasa.gov/docs/slrover.pdf

(Ref.7) https://www.haystack.mit.edu/edu/pcr/Data/pdf/Introduction%20to%20plate%20tectonics,%20geodesy%20and%20VLBI-final.pdf

(Ref. 8) https://cimss.ssec.wisc.edu/sage/geology/lesson2/concepts.html

(Ref. 9) https://onlinelibrary.wiley.com/doi/abs/10.1111/ter.12283

(Ref. 10) http://www.planetary.org/blogs/jason-davis/2017/20170612-falklands-impact-crater.html


# Nicolas Coltice

Ecole Normale Supérieure de Paris (France)

www.augury.eu


## Education

2001 – PhD at Ecole Normale Supérieure de Lyon (France): Dynamics of the Earth's interior and volatile elements. Advisor: Philippe Gillet.

## Career

| | |
|---|---|
| Professor, Geosciences Department – Ecole Normale Supérieure | 2018-present |
| Professor, Earth Sciences Department – University of Lyon | 2012-2018 |
| Director, iCAP (teaching and learning service) icap.univ-lyon1.fr | 2008-2010 |
| Lecturer, Earth Sciences Department – University of Lyon | 2002-2011 |
| French civil service (scientist) Princeton University (USA) | 2001-2002 |

## Research interests

– *Mantle convection.* Determining the nature of mantle dynamics and its evolution through time using theories and numerical models together with geological observations.

– *Lithosphere dynamics.* Understanding the nature of Earth tectonics and the relationships between the deep Earth and the surface environment with thermo-mechanical models of the lithosphere and coupled mantle-lithosphere system.

– *Early Earth.* Building models to quantitatively study processes responsible for the differentiation and early evolution of the Earth and planets.

– *Geochemistry.* Identifying the processes at play in the long-term dynamic evolution of Earth's envelopes (core, mantle, crust and exosphere) thanks to models coupling geochemistry and geophysics.

## Publications and Services

– **Coltice, N.**, Gérault, M., Ulvrova, M. (2017). A mantle convection perspective on global tectonics. Earth Sci. Rev. 165, 120-150.

– Mallard, C., **Coltice, N.**, Seton, M., Müller, R. D., & Tackley, P. J. (2016). Subduction controls the distribution and fragmentation of Earth's tectonic plates. Nature 535, 140-143.

– Rey, P. F., **Coltice, N.,** & Flament, N. (2014). Spreading continents kick-started plate tectonics. Nature 513, 405-408.

– **Coltice, N.**, Rolf, T., Tackley, P. J., & Labrosse, S. (2012). Dynamic causes of the relation between area and age of the ocean floor. Science, 336(6079), 335-338.

– Geosciences 3D (http://geosciences3d.univ-lyon1.fr): a project for the production of 3D didactic digital resources to teach Earth Sciences (in collaboration with M.I.T. and Institut Français d'Education).

– *Hy-SUP* (ERASMUS project modernization of higher education). This European work aimed at providing new perspectives for teaching using hybrid environments (use of technologies). http://prac-hysup.univ-lyon1.fr/

– Did this really happen (didthisreallyhappen.net)? A project to grow awareness on sexism in sciences.

## Awards nd Honors

- *Editors' Citation for Excellence in Refereeing* - Geochemistry, Geophysics, Geosystems (2016).
- *ERC consolidator Laureate* (2014-2019).
- *Junior member of Institut Universitaire de France* (2011-2016).
- *Grand prize Higher education* - EDUCATICE 2012 (3DAnatomy-Geosciences3D). Awarded by the Ministry of Education every year to a project of particular innovative interest using technologies for teaching and learning.
- *First prize of C.N.F.G* (2002). Awarded every 2 years to one deep Earth PhD obtained in France.

# SOME SHAPES OF PLATE TECTONICS TO COME

**Nicolas Coltice**
Ecole Normale Supérieure de Paris, France

For the past 50 years, the Earth science community has tried to expand the theory of plate tectonics beyond its limits. The simplicity of its essence, rigid blocks moving on a sphere, allowed rapid progress in reconstructing the motion of the Earth surface. Plate reconstructions have stretched out their fabulous potential to deeper times (back to the Proterozoic), and connected to other global scientific questions, like carbon cycling. But the intrinsic limitations of plate tectonics still persist today. They are (a) an over-dependence on seafloor data which makes uncertainties of plate reconstructions beyond 50~Ma difficult to realize with accuracy, (b) more complex types of plate boundaries are needed, and (c) plates are not completely rigid, especially in the interesting places for geologists (mountains, rifts, pull apart basins).

To go beyond these issues, the community is actively testing "augmented" plate tectonics frameworks, adding new observations and new pieces of theory to move past the limitations. Classical observations for plate tectonic reconstructions focus on the Earth surface: elevation, earthquakes, volcanoes, ophiolites, metamorphic blocks, sedimentary groups, geodesy, marine geophysics, fossils and paleomagnetic data (seafloor and continental). Looking deeper in the mantle adds new information allowing us to go back in time and reconstruct the history of buried ancient seafloor. With the development of seismic tomography, geoscientists have been hunting slabs down to the lower mantle. The difficulties with such observations come from understanding how to unfold them back in time to the surface.

Large Low Shear Velocity Provinces (LLSVPs) lying atop the core-mantle boundary are another seismic tomography feature that can provide constraints to plate reconstructions. If plumes do rise from their borders, which is suspected, the location of hotspots and plume-related magmatic provinces give the position of large igneous provinces and their respective plates, relative to these crypto-continents. Assuming LLSVPs are fixed provides a way to constrain surface kinematics back in time, as long as there are plume-related magmatic provinces in the geologic record. However, the fixity assumption is controversial.

Hence, the time limitation remains to be overcome. Also, the original definition of 3 types of plate boundary seems restrictive. New types of plate boundary have been proposed to explain broad scale deformation like between India and Australia, or for wide mountain belts like the Himalayas. They are called diffuse plate boundaries. The issue is that diffuse deformation involves mechanical properties of the lithosphere at some point, and it remains difficult to model them.

The third limitation is plate rigidity. Indeed, plates are often made of heterogeneous blocks under stresses, and show non-neglible seismicity inside them. Considering the mechanical behavior of rocks releases the plate rigidity constraint. Rigidity should emerge naturally from a dynamic feedback between tectonic forces and strain localization. But the rheology of the lithosphere is uncertain, and remains a challenge for physics and modeling (both numerical and experimental). However, several groups try to define lithosphere motion in a fully dynamic framework, using rheologies (viscous or viscoelastic) that localise deformation, depending on stress and sometimes on strain/strain-rate.

Every approach to overcome limitations of plate tectonics works against the rarity of information on the state of the mantle-lithosphere system. Most of them involve dynamic consideration on how plate boundaries evolve, or how convective instabilities sink or rise. The crux is that the mantle and the lithosphere make a complex system, where multiple feedbacks between scales produce the convective flow and tectonics altogether. Since 1998, geodynamicists have developed numerical models that give access to self-organisation of tectonic plates. The step forward was the possibility of solving mantle convection equations taking into account some of the complexity of rock mechanics. These models (see Figure 1) produce several key emergent properties that closely match kinematic and tectonic observations: seafloor age-area distribution, supercontinent cycles, plate size distribution, continental vs. oceanic plate velocities, coexistence of multiple scales of convection and topography. These models can be combined with inverse methods or machine learning to bring new insights into tectonic reconstructions, sometimes even without the help of plate tectonics theory.

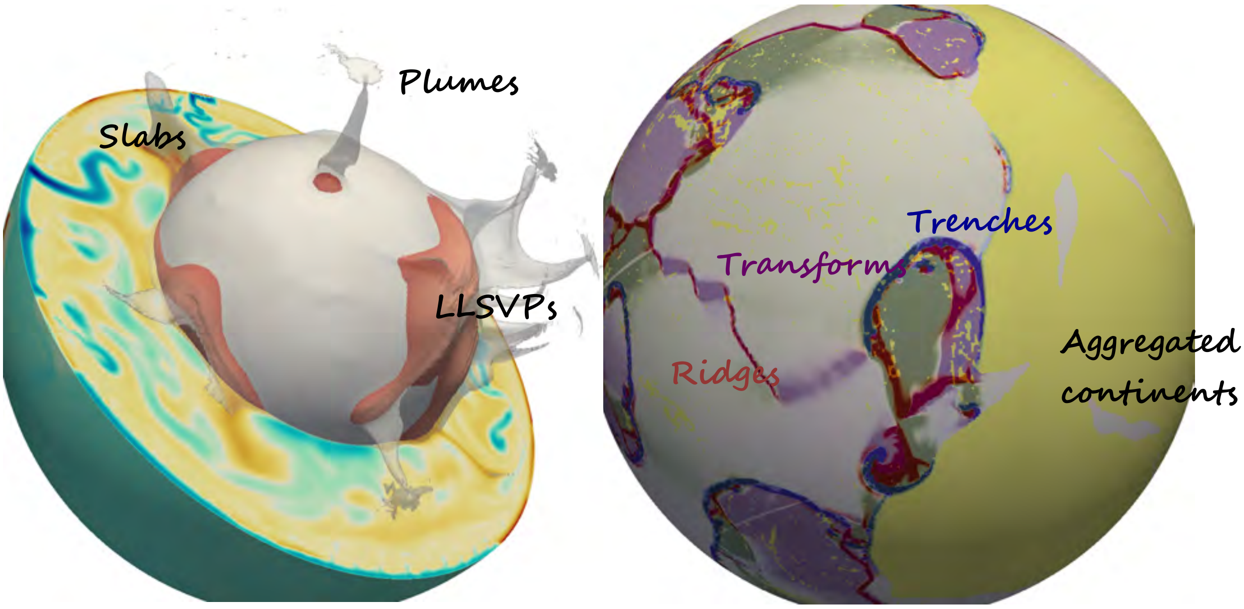


***Figure 1:*** *Example of a convection model with plate-like behaviour. On the left, the temperature field shows the sinking of slabs and rise of plumes (white isotherm). The red isocontour shows modelled LLSVPs. On the right, the yellow region show modelled continents. Blue displays trenches, red ridges. The color field going from purple to green displays the vorticity at the surface, which corresponds to transform motion and plate spin.*

**Geological trail**
**from Maria Theresa's Monument**
**to St. Stephen's Cathedral**
**$10^{th}$ April 2019, 14.30 – 16.00**