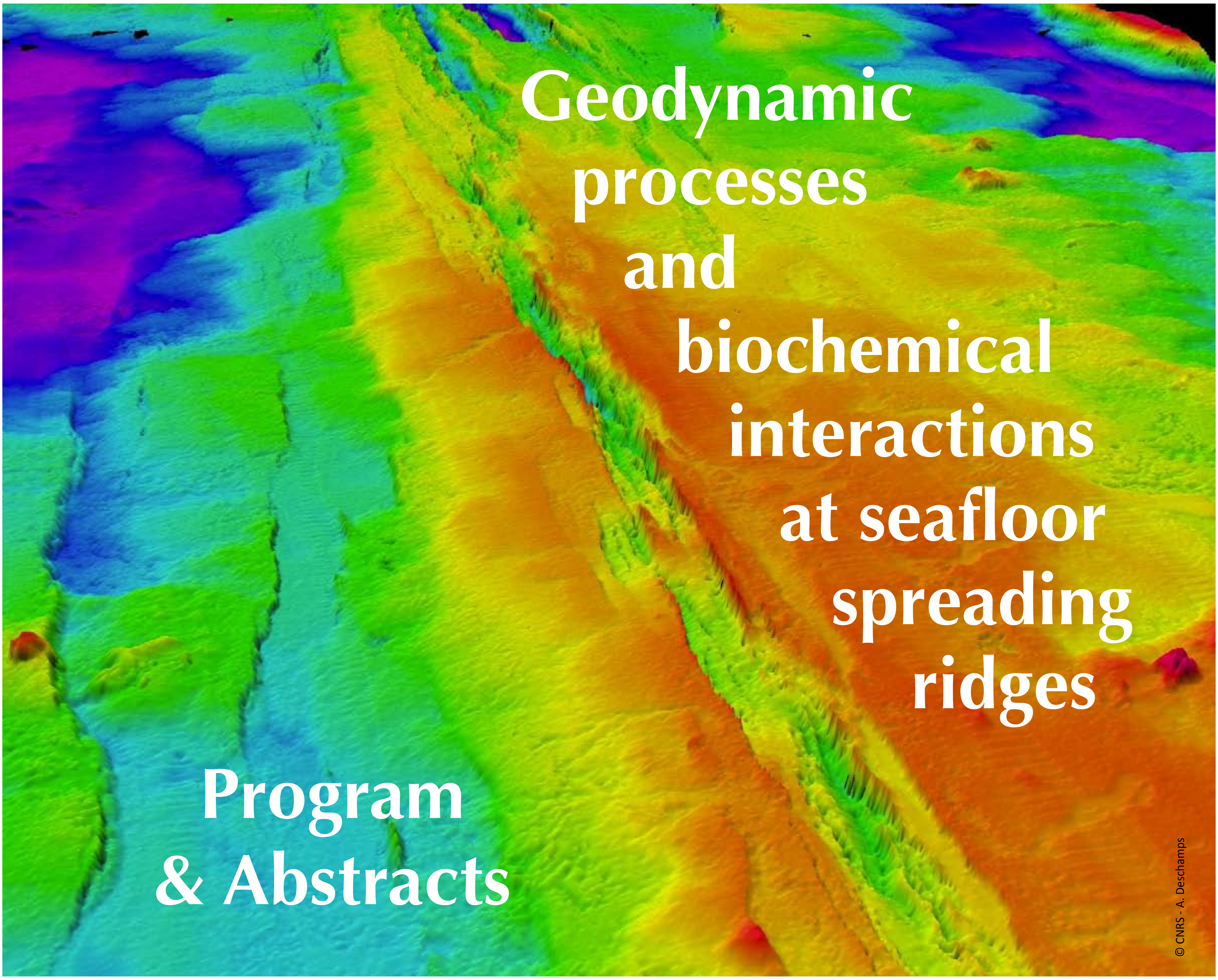
GEOCEAN

Symposium Jean Francheteau & Summer School
August 27-31, 2012 - Brest, France



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GEOPHYSICISTS

Jean Francheteau (1943–2010)

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Jean Francheteau, pioneering marine geologist and geophysicist, AGU Fellow, and emeritus professor at the University of Brest (Université de Bretagne Occidentale), died on 21 July in St-Renan, Brittany, France, at the age of 67 after a long illness. With his passing, the field of Earth sciences lost a major contributor to the development of a definitive theory of plate tectonics and one of the first to make visual geological observations on the deep seafloor. Such scientific accomplishments, coupled with his personal charm and the ability to collaborate with researchers from many institutions, ensured that he had a huge influence not only on the world of research but also on teaching and the application of ethics to science.

Jean arrived at Scripps Institution of Oceanography in La Jolla, Calif., in 1966 after obtaining a diploma in mining engineering at the prestigious École Nationale Supérieure de la Métallurgie et de l'Industrie des Mines in Nancy, France. He chose Victor Vacquier as his thesis supervisor and began working in Vic's lab with John Sclater, ostensibly on heat flow measurements.

Jean had a defining effect on this research program, moving it very far from heat flow. As a second-year graduate student he persuaded Harmon Craig, a seagoing geochemist, to devote 2 days of his precious shipboard sampling time to the topographic and magnetic surveys of two adjacent major seamounts in the central Pacific; these runs ultimately yielded excellent magnetic pole positions. After hearing a talk on the 1967 *Nature* paper (*216,* 1276–1280) by Dan McKenzie and Bob Parker quantifying Tuzo Wilson's theory of rigid plates, Jean looked around for tectonic problems in the oceans to examine from a quantitative approach. First, he tackled the stability of the finite rotation poles that describe the motion of the Pacific plate by examining the trends of the major North Pacific fracture zones. Next, he and John Sclater decided to investigate the arguments—raised by Russian publications—that the apparent equality of heat flow between oceans and continents presented a serious problem to the overall theory of plate tectonics. In contrast, they were able to show that the existing heat flow data and the subsidence of the mid-ocean ridges both bore simple relationships with the age of the ocean floor that actually strongly supported the theory.

Following these publications, Vacquier and Sclater left for 3 months at sea, expecting that Jean would integrate all of his already published papers as his doctoral thesis. But, instead, they found that in their absence, Jean had prepared as his thesis a global examination of paleomagnetism and plate tectonics without a single reference to his five already published papers!

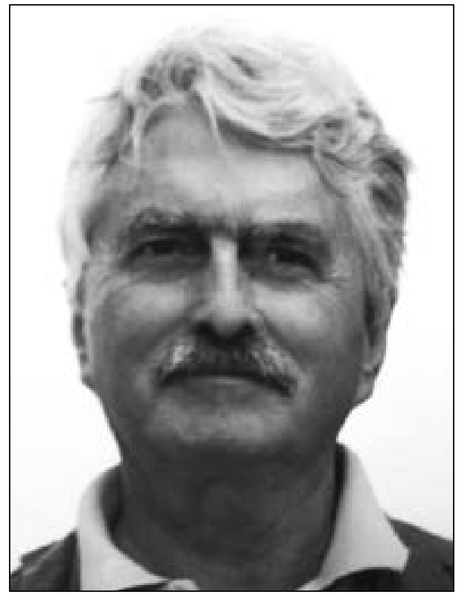
Jean left Scripps at age 27, with an international reputation and an understanding of marine science at the highest level, to return to Brittany, where he had spent his childhood. He joined the new Center of Oceanography in Brittany (COB), where Xavier Le Pichon had assembled a team of highly regarded marine geologists and geophysicists. After 2 years of intense effort, Jean and Le Pichon, together with Jean Bonin, authored a book, *Plate Tectonics*, which was the first book that captured both the conceptualization and the application of the theory of plate tectonics. In a published review of this book, Fred Vine wrote, "I find it impossible to find fault with this book," incredibly high praise from this eminent British scientist. The authors followed this with a series of seminars and educational courses that were highly regarded nationally.

While at COB, Jean was heavily involved in submersible research on the Mid-Atlantic Ridge. He was a leader in the French-American Mid-Ocean Undersea Study (FAMOUS) expeditions in 1973 and 1974 that made early integrated deep-sea observations along the Mid-Atlantic Ridge near the Azores. This was the beginning of true, visual geological exploration of the oceans.

From 1978 through 1983, Jean was a major player in notably productive dives using French and American submersibles and the lead author on several papers that reported the discovery of active hydrothermal sites and identifiable mineral deposits with associated ecosystems at the crest of the East Pacific Rise. He left Brittany in 1981 to move to the Institut de Physique du Globe de Paris, where he led the marine group participating in significant oceanographic expeditions along the Pacific spreading centers. Key parts of these observations were made using submersibles, including a bathyscaphe.

In 1992, Jean returned to Brest, this time as a professor of geophysics at the University of Brest. He chaired the doctoral school in marine sciences there from 1999 to 2007. He also led the research program on spreading ridges at the European Institute for Marine Studies at the Centre National de la Recherche Scientifique (CNRS) from 1991 to 1998.

Jean coauthored more than 90 papers and a major textbook. He made fundamental contributions to plate tectonics and modern marine geology and geophysics. In the



Jean Francheteau

Earth sciences, his work had an incredible range, covering paleomagnetism, plate kinematics, heat flow, hydrothermal circulation, the structure of continental rifts and oceanic spreading centers, oceanic fracture zones, seamounts, and rock magnetism. He ventured and researched all over the world, from the depths of the Atlantic and Pacific oceans to the heat of the Afar Depression (in northeastern Africa) and the heights of Tibet.

Through his research and his editorial activities (he served as editor of *Geophysical Journal International* from 1988 to 2010), Jean had an encyclopedic knowledge of oceanography that was tapped extensively by every colleague who had the opportunity to work with him. He received many international honors, including Fellow of the Royal Astronomical Society (1974), Fellow of the American Geophysical Union (1984), CNRS Silver Medal (1982), and the Grand Prize in Marine Sciences (1995) from the French Academy of Sciences.

In 1970, Jean married Marta Lerrick, who moved with him to Brest, where they settled into a marvelous old house in Locmaria-Plouzané with their (ultimately) five children. Jean was the complete scientist: a superbly trained French engineer, a key participant in one of the major revolutions in the Earth sciences, a marvelous seagoing colleague, a great leader of expeditions, and a major participator in a series of nationally broadcast conferences on science and ethics. With his charm, modesty, and willingness to collaborate and share data with associates around the world, Jean was a gifted ambassador of all that was best in French research.

—JOHN SCLATER, Scripps Institution of Oceanography, University of California, San Diego, La Jolla; E-mail: jsclater@ucsd.edu; and XAVIER LE PICHON, Collège de France, Aix en Provence, France

Selection of Jean Francheteau's publications (> 90)

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Naar, D.F., R. Hekinian, M. Segonzac & J. Francheteau, **2004**. Vigorous venting and biology at Pito Seamount, easter microplate. *In Mid-Ocean Ridges: Hydrothermal Interactions Between The Lithosphere and Oceans*, *Geophysical Monograph Series*, **148**: 305-318.

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Symposium

Monday August 27, 2012 (Amphi A, IUEM)

8h30	**Welcome & Registration**

Session 1: In memory of our colleague and friend Jean Francheteau

9h00	**Jean-Yves Royer, Pascal Gente (Univ. Brest), Jean-François Stéphan (INSU CNRS) and Sarah Francheteau-Berman** *Welcome address*
9h30	**Xavier Le Pichon (Collège de France, Aix-en-Provence)** *From Paleomagnetism to Plate tectonics, the contribution of Jean Francheteau to the discovery of finite Plate tectonics*
10h00	**W. Jason Morgan (Princeton Univ.)** *Jean Francheteau and plate reconstructions*
10h30	Coffee Break
11h00	**Pierre Choukroune (Univ. Aix-Marseille)** *When did Plate Tectonics start ?*
11h30	**Richard Hey (Univ. Hawaii), Fernando Martinez, Asdis Benediktsdóttir & Armann Höskuldsson** *Jean Francheteau & Seafloor Spreading Reorganizations: Microplates, Propagators, Overlappers & Iceland*
12h00	**Claude Rangin (CEREGE, Aix-en-Provence)** *"Déchirures": Continental Break-up & Tear-off*
12h30	Lunch Break at IUEM

Session 2: Plate tectonics: kinematics & thermo-mechanical evolution of plates

14h00	**Robert Ballard (URI Center for Ocean Exploration), *live from E/V Nautilus*** *Dr. Jean Francheteau's Contribution to the Study of the Earth*
14h30	**Richard Gordon (Rice Univ. , Houston TX) & Jay K. Mishra** *Current global plate motions: Shrinking plates & transform faults*
15h00	**Claude Jaupart (Institut de Physique du Globe de Paris)** *Thermal Structure and Stability of Thick Continental Lithosphere*
15h30	**Michel Diament (Institut de Physique du Globe de Paris)** *Intraplate volcanism in the South Pacific, what have we learned from satellites ?*
16h00	Coffee Break
16h30	**Emile Okal (Northwestern Univ., Evanston IL)** *T-waves: guardians of hidden ocean processes*
17h00	**Louis Géli (Ifremer, Brest)** *Earthquake precursors and supercritical fluids at oceanic fracture zones*
17h30	**Yossi Mart (Univ. Haifa)** *The life cycle of back-arc basins: an experimental approach*
18h00	End of Session
	Transportation to Oceanopolis
19h00	Dinner at Oceanopolis

Tuesday August 28, 2012 (Amphi A, IUEM)

Session 3: Processes at seafloor spreading centers

9h00	**Thierry Juteau (Univ. Brest)** *Ophiolites and oceanic crust : the permanent dialog*
9h30	**Catherine Mével (Institut de Physique du Globe de Paris)** *Drilling the oceanic lithosphere*
10h00	**Mathilde Cannat (Institut de Physique du Globe de Paris)** *Axial-valley bounding faults and the exhumation of mantle-derived rocks at slow spreading ridges*
10h30	Coffee Break
11h00	**Alessio Sanfilippo (Univ. di Pavia) & Riccardo Tribuzio** *Building of the deepest gabbroic crust at a fossil slow spreading centre (Pineto gabbroic sequence, Alpine Jurassic ophiolites)*
11h30	**Lily Muller (PhD, Univ. Oxford) & Anthony Watts** *Seamount morphology and structure of the Southwest Indian Ridge (40°E - 60°E)*
12h00	**Michael Perfit (University of Florida, Gainesville FL)** *Mid-Ocean Ridge Volcanism on the East Pacific Rise: Integrated Volcanologic, Geophysical and Geochemical Studies*
12h30	Lunch Break at IUEM
14h00	**Jason Phipps Morgan (Univ. Cornell, Ithaca NY)** *A dynamic theory for the morphology of Overlapping Spreading Centers*
14h30	**Lars Rüpke (Helmholtz Center for Ocean Research, Kiel), Sonja Theissen-Krah, Karthik Iyer & Jason Phipps Morgan** *Crustal accretion and hydrothermal convection patterns at fast-spreading ridges*
15h00	**Anne Deschamps (European Institute for Marine Studies, Brest), Morgane Le Saout, Adam Soule, Pascal Allemand, Brigitte Van Vliet Lanoe & Christophe Delacourt** *Submarine and aerial inflated lava flows*
15h30	**Poster presentations** *5 minutes / poster*
16h30	Final address, Coffee Break & Poster session

Cécile Grigné (European Institute for Marine Studies, Brest), Chantal Tisseau, Manuel Combes, Marc Parenthoën, Sébastien Le Yaouanq & Jacques Tisseau
Multi-agent modeling of Earth's dynamics

Hailong Bai (PhD, Univ. Maryland, College Park MD), Laurent Montesi & Laura Hebert
Origin of Crustal Thickness Anomalies at Oceanic Transform Faults

Briais Anne (Obs. Midi-Pyrénées, Toulouse), Olga Gomez & Raymond Lataste
Off-axis seamounts on the flanks of the Southeast Indian Ridge. Implications for mantle dynamics east of the Australia-Antarctic Discordance.

Morgane Le Saout (PhD, Univ. Brest), Anne Deschamps, Adam Soule, Pascal Allemand & Pascal Gente
Lava flows morphologies at the intersection of the East-Pacific Rise with the Mathematician hot-spot, 16° N.

Christine Andersen (PhD, Univ. Kiel), Lars Rüpke & Sven Petersen
Tectono-magmatic controls on hydrothermal activity at the Mid-Atlantic Ridge vent fields Logatchev and 5°S

Thibaut Barreyre (PhD, IPG Paris), Javier Escartin, Rafael Garcia & Mathilde Cannat
Structure and temporal variation in fluid outflow at the deep-sea Lucky Strike hydrothermal field (Mid-Atlantic Ridge) from seafloor imagery and temperature records

Rosa-Maria Prol-Ledesma (PhD, UNAM Mexico) & Marco Antonio Torres-Vera
Large scale hydrothermal flow in a sedimented spreading center in the northern gulf of California, Mexico

Guy Evans (PhD, MIT/WHOI) & Margaret Tivey
Geochemical and Morphological Diversity of Vent Deposits from the Lau Back-arc Basin Arising from Variations in Igneous Rock Composition and Volcanic Arc Influence

Bleuenn Gueguen (PhD, Univ. Brest), Olivier Rouxel & Yves Fouquet
Ni isotope in ferromanganese crusts and deep-sea-clays: hydrogenetic and authigenic precipitation of Mn-oxides

Stéphane Roumējon (PhD, IPG Paris) & Mathilde Cannat
Tectonic initiation of serpentinization: mesh-texture development, in exhumed peridotites, at slow and ultraslow-spreading ridges

Margaret Tivey (Woods Hole Oceanographic Institution, MA) & Anna-Louise Reysenbach
Use of thermocouple arrays for study of microbial colonization in very young (days to weeks old) vent deposits

Pauline Henri (PhD, IPG Paris), Céline Rommevaux-Jestin, Bénédicte Menez & Françoise Lesongeur
Basalt alteration by endemic microorganisms of hydrothermal vents

Maria-Cristina Ciobanu (Ifremer, Brest)
Microbial diversity of marine sediments from the Canterbury Basin, New Zealand (IODP Leg 317)

Nolwenn Callac (PhD, Univ. Brest), Olivier Rouxel, Françoise Lesongeur, Carole Decker, Céline Liorzou, Claire Bassoullet, Karine Estève, Patricia Pignet, Sandrine Cheron, Joel Etoubleau, Yves Fouquet, Céline Rommevaux-Jestin & Anne Godfroy
Continuous enrichment culture using diluted hydrothermal fluid as medium: insights into sulfur and iron biogeochemical cycles, microbial actors, and mineral interactions in active deep-sea vent chimney of Guaymas Basin

18h00	End of Symposium

Summer School

Wednesday August 29, 2012 (Amphi B, IUEM)

8h45	**Olivier Rouxel & Jean-Yves Royer** *Welcome at IUEM and logistics*
9h15	**Debbie Milton (NOC, Southampton)** *InterRidge*

Session 1: Geodynamics & petro-geochemical processes at seafloor spreading ridges and ridge flanks

9h45	**Michael Perfit (Univ. Florida, Gainesville FL)** *Crustal accretion and petro-geochemical processes at seafloor spreading ridges*
10h45	Coffee Break
11h00	**Benoit Ildefonse (Geosciences, Montpellier)** *Formation and evolution of the oceanic lithosphere*
12h00	**Wolfgang Bach (University of Bremen)** *Alteration of the Oceanic Lithosphere and Implications for Seafloor Processes*
13h00	Lunch Break at ENSTB
14h00	**TRAINING SESSION A (2 groups) PC rooms; IUEM** *A1: Geodynamic modeling: Anne Deschamps (IUEM, Brest)* *A2: Logging techniques: Louise Anderson (University of Leicester)*
16h00	**TRAINING SESSION B (2 groups) IUEM; LDO conference room (include coffee break)** *B1: Petrological description / Macro description: W. Bach / B. Ildefonse* *B2: Petrological description / Microscope: G. Chazot (IUEM, Brest)*
18h00	End of day

Thursday August 30, 2012 (Salon de l'océan, Ifremer)

8h45	**Welcome at Ifremer and program of the day**

Session 2: Fluid-rock interactions & geochemistry of seafloor hydrothermal systems

8h55	**Yves Fouquet (Ifremer, Brest)** *Seafloor hydrothermal systems and mineral resources at the seafloor*
9h45	**Margaret Tivey (Woods Hole Oceanographic Institution, MA)** *Geochemical modeling of vent environments*
10h45	Coffee Break
11h00	**TRAINING SESSION C (2 groups)** *Crustal accretion and petro-geochemical processes at seafloor spreading ridges* *C1: Sulfide/mineral deposits at seafloor: Yves Fouquet (Ifremer)* *C2: Geochemical techniques : J.-A. Barrat (IUEM, Brest) &Olivier Rouxel (Ifremer)*
13h00	Lunch Break at Ifremer
14h00	**Brian Glazer (Univ. Hawaii)** *Microbial geochemistry of deep sea hydrothermal iron*
14h45	**Brandy Toner (Univ. Minnesota, Mineapolis MN)** *How to use X-ray absorption spectroscopy to measure Fe, Mn, and S in marine particles*
15h30	Coffee Break
16h00	**TRAINING SESSION D (2 groups)** *D1: Spectroscopy: Brandy Toner (Univ. Minnesota), at La Pérouse Library* *D2: In-situ measurements: Brian Glazer (Univ. Hawaii)*
18h00	End of day

Friday August 31, 2012 (Amphi B, IUEM)

Session 3: Geobiological interactions in extreme environments

8h45	**Stefan Lalonde (IUEM, Brest)** *Introduction to geobiology*
9h45	**Olivier Rouxel (Ifremer, Brest)** *Isotopic evidence for microbial activity in rocks*
10h45	Coffee Break
11h00	**Anne Godfroy (Ifremer, Brest)** *Microbial life in hydrothermal active chimneys*
11h45	**Pierre-Marie Sarradin (Ifremer, Brest)** *Deep-sea ecosystems and habitat characterization*
12h30	Lunch Break at ENSTB

Session 4: Concluding session

14h00	*Roundtable: three-session restitution addressing, for each theme, the following questions:* *- What are, in your view, the overall "big-picture" scientific questions ?* *- What are the most significant future research directions ?* *- What technological/methodological advances will most improve our understanding ?* **Discussion leaders: O. Rouxel and S. Lalonde**
15h30	Coffee Break
16h00	**Lucie Roa (Cellule Europe UBO)** *Research opportunities for students and postdocs in Europe*
16h30	Final address and end of GEOCEAN Summer School

Authors Index

Tectono-magmatic controls on hydrothermal activity at the Mid-Atlantic Ridge vent fields Logatchev and 5°S

Andersen Christine [1*], Rüpke Lars [1], Petersen Sven [1]

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We are investigating the relationships between tectono-magmatic processes at slow spreading ridges and the origin and nature of hydrothermal circulation. In particular, we will test if off-axis venting is a natural consequence of seafloor spreading in a tectonic phase, while on-axis venting occurs during magmatic dominated phases.

Background & Motivation

Slow spreading ridge segments undergo shifting periods of magmatic and tectonic phases (e.g. Escartin et al., 2008). Hydrothermal venting frequently occurs in off-axis regions as in the ultramafic hosted Logatchev hydrothermal field (e.g. Petersen et al., 2009). There a swarm of high seismicity events has been recorded a couple of km off-axis, suggesting intense tectonic deformation along fault planes that are dipping towards the ridge axis. Even if tectonic activity is common along the MAR, some ridge segments show evident recent, magmatic activity and hydrothermal springs in the axial region. In the 5°S field seismic events, related to magmatic processes, as well as fresh basaltic lava flows have been observed along the ridge axis (Haase et al., 2007). The contrasting styles of seafloor spreading and hydrothermal venting of the two described MAR systems Logatchev and 5°S make them ideal case studies for testing our key hypothesis about the tectono-magmatic state of slow spreading ridges controlling hydrothermal vent field location.

Modeling of seafloor spreading mechanics

We are currently developing a 2D lithosphere scale numerical model that resolves incompressible visco-elasto-plastic deformation of the seafloor at slow-spreading conditions. We use a Finite Element approach based on the MILAMIN solver with an unstructured, deforming, langrangian grid that consists of triangular seven-node elements. We are working on the implementation of plastic deformation in the code using the Mohr Coulomb yield stress formulation as in Kaus, (2010), including strain weakening. A key difficulty of incompressible codes is to handle volume changes, which occur in the zone of magmatic accretion in our model. Magma injection will be solved by the implementation of a dilation term like in Theissen-Krah et al., (2011).

Results

We will present the control of varying rates of magma supply to slow spreading ridge segments on the mechanics of seafloor extension. The outcomes from the mechanical model are expected to be similar to the ones of Buck et al., (2005). Moreover we will compare our results to the available seismic data on the Logatchev field. Two likely end-member scenarios are:
a) Phases of high magma supply, where the amount of magma added to the system is in equilibrium with the amount of oceanic lithosphere leaving the system due to extension of the seafloor. During this set-up the ridge is expected to behave similar to fast-spreading conditions with seafloor spreading occurring via crustal accretion and low degrees of faulting. These magmatic conditions are favorable for active hydrothermal venting along the ridge axis as seen at 5°S.
b) Phases of low magma supply, where the amount of magma added to the system is lower than the amount of oceanic lithosphere leaving it. This disequilibrium triggers intense tectonic activity, including brittle deformation and the development of large scale detachment faults reaching the surface in off-axis regions. Under these conditions spreading of the oceanic lithosphere happens via tectonic extension instead of magmatic crustal accretion. Hydrothermal circulation is expected to occur along fault structures with active springs in off-axis regions as observed in the Logatchev field.
We are using the above mechanical model in order to understand the large scale thermal and deformation fields and will use the outcomes as input for the hydrothermal model we will develop. Fully coupled simulations of deformation and fluid flow remain challenging. The different timescales of the two processes and the fact that hydrothermal systems are already intrinsically multi-phase pose significant difficulties.

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Origin of Crustal Thickness Anomalies at Oceanic Transform Faults

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Crustal thickness differences between oceanic transform faults and spreading centers may reflect melt migration and extraction processes. It has been suggested that at oceanic transform faults, the effective conductive cooling will direct melt generated at mid-ocean ridges away and result in thin crust. At slow spreading ridges, transform faults are indeed characterized by more positive gravity anomalies than the adjacent ridge segments, indicating crustal thinning in the transform domain. However, recent geophysical studies have shown that intermediate and fast-slipping transform faults exhibit more negative gravity anomalies than the ridge proper, indicating crustal thickening in the transform domain. Such crustal thickness variations suggest that melt is redistributed at fast-spreading ridges towards the transform fault, but not at slow spreading ridges. At mid-ocean ridges, melt is generated by decompression as a result of the divergence of the plates. It is extracted from the mantle to form the oceanic crust. Melt extraction can be seen as a three-step process. 1) Melt moves vertically under its buoyancy in the partial melting region through a combination of porous flow and connected dissolution channels. 2) Melt accumulates at and moves along a low permeability barrier located at the base of the plate. 3) Melt may enter a melt extraction zone around the plate boundary where it gets extracted to the surface and contributes to the crustal thickness. Recent publications have shown that these three steps are able to explain crustal thickness variations at both ultraslow and ultrafast spreading centers.
We hypothesize that, through its effects on the thermal structure of the transform domain, spreading rate controls whether the permeability barrier intersects the melt extraction zone within the transform domain. At fast ridges, the permeability barrier is relatively shallow and intersects the melt extraction zone underneath transform fault. Melt can be extracted, resulting in thickened crust in the transform domain. At slow ridges, the permeability barrier is deeper than the melt extraction zone, and melt cannot be extracted at the transform domain, resulting in a thin crust. Three-dimensional numerical models of melt migration and extraction along oceanic transform domains using the commercial finite element software COMSOL Multiphysics® and Matlab lead to prediction of crustal thickness variations that can be compared with observations. The actual geometry of transform faults and the transform segmentation will be included in the model. Preliminary results show thick crust is predicted in the transform domain for spreading rates larger than 5 cm/yr full rate is the melt extraction zone reaches 25 to 30 km depth, which is consistent with other models of melt extraction at the ultraslow Southwest Indian Ridge.

Dr. Jean Francheteau' Contribution to the Study of the Earth

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I first began working with Dr. Jean Francheteau during Project FAMOUS; the French-American Mid-Ocean Undersea Study, which had its roots in the January, 1972 Princeton Workshop sponsored by the American National Academy of Sciences.

The Theory of Plate Tectonic was still in its infancy when the earth scientists of the world assembled in Princeton to discuss how best to test this exciting new theory in the field.

Manned submersible were also in their infancy but despite their lackluster track record at the time, it was decided to use them in a comprehensive field-mapping program along a «typical » spreading segment of the Mid-Atlantic Ridge at a depth of 3,000 meters, using the French bathyscaphe ARCHIMEDE and their new submersible CYANA along with the American submersible ALVIN, which has just received its new titanium hull.

The lead institutions for this program were the Woods Hole Oceanographic Institution in America, better known as WHOI and the Center National for the Exploitation of the Oceans better known as CNEXO.

The planning and preparations that went into these first dives into the Mid-Ocean Ridge were intense; characterized by numerous meetings between these two organizations headed up by Dr. Jim Heirtzler from WHOI and Dr. Xavier Le Pichon and Claude Riffaud from CNEXO. At the conclusion of every meeting, a detailed report of the meeting's results had to be written. That task fell to the two youngest scientists making up the two teams; myself for America and Jean for France.

Jean had just completed his Ph.D. at the Scripps Institute of Oceanography and was now on the staff at CNEXO's new Centre Oceanologique de Bretagne or COB in Brest, France and I was finishing up my Ph.D. and was just transferring from the ALVIN Group at WHOI to its Department of Marine Geology and Geophysics.

Over the next fifteen years, Jean and I participated in numerous expeditions to the Mid-Ocean Ridge in the Atlantic and Pacific Ocean Basins resulting in more than fourteen papers in referred journals. Our focus was on the volcanic, tectonic, and hydrothermal processes of the ridge axis having slow to ultra-high spreading rates.

Many things impressed me about Jean, the first being his command of both the geological and geophysical worlds, easily bridging the gap others could not bridge. He had a strong background in the physics of the earth sciences but also was an excellent field geologist. These strengths coupled with his unpretentious humility and ever-present smile made working with him a great learning and at the same time delightful experience.

The most important papers we would write together came near the end of our long collaboration, after countless months at sea exploring the Mid-Ocean Ridge using every tool at our deposal. From these studies, a pattern in the volcanic, tectonic, and hydrothermal processes occurring along the axis of the Mid-Ocean Ridge's spreading centers began to emerge. Using the detailed morphology of a spreading axis obtained using multi-narrow beam sonar bathymetry, our model could be used to predict where active hydrothermal vents might be located, the types of lava flows that might be encountered, and nature of tensional fracturing in the newly formed brittle crust along the MOR axis.

Structure and temporal variation in fluid outflow at the deep-sea Lucky Strike hydrothermal field (Mid-Atlantic Ridge) from seafloor imagery and temperature records

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Hydrothermal activity along mid-ocean ridges accounts for a large proportion of the Earth's heat loss and support unique deep-sea ecosystems. To date, accurate quantification of the heat flux at individual sites remains problematic. As a first step, we have focused on the study of one of the largest known hydrothermal fields (Lucky Strike, Mid-Atlantic Ridge), to study the structure, the temporal variability and the dynamics of hydrothermal outflow from seafloor imagery and temperature records. We demonstrate that image mosaicing over large seafloor areas is now feasible with new image processing techniques, and that repeated surveys can be used for temporal studies of active processes. Lucky Strike mosaics, generated from >56,000 images acquired in 1996, 2006, 2008 and 2009, reveal the distribution and types of diffuse outflow throughout the field, and their association with high-temperature vents. In detail, the zones of outflow are largely controlled by faults, but we suggest that the spatial clustering of active zones likely reflects the underlying geometry of the plumbing system. Imagery also provides constraints on temporal variability at two time-scales. First, based upon changes in individual outflow features identified in mosaics acquired in different years, we document a general decline of diffuse outflow throughout the vent field over time-scales ranging from 1 to 13 years. Second, the image mosaics reveal broad patches of seafloor that we interpret as fossil outflow zones, owing to their association with extinct chimneys and hydrothermal deposits. These areas also encompass the entire region of present-day outflow, suggesting that the plumbing system has remained stable over geological time. The interpretation of the mosaics coupled with field measurements allow us to put forward an estimate of the heat flux of the Lucky Strike system that ranges from 200 to 1000 MW, with 75 % to >90 % of the flux taken up by diffuse hydrothermal outflow. Based on these heat flux estimates, we propose that the temporal decline of the system at short and geological time scales may be explained by the progressive cooling of the AMC, lacking any replenishment. The results at Lucky Strike demonstrate that repeated image surveys with adequate processing can be routinely performed to characterize and study the temporal variability of a broad range sites hosting active processes (e.g., cold seeps, hydrothermal fields, gas outflows, etc.), opening the possibility to better understand the dynamics of fluid flow in the sub-seafloor, as well as the quantification of fluxes.

Off-axis seamounts on the flanks of the Southeast Indian Ridge. Implications for mantle dynamics east of the Australia-Antarctic Discordance.

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We have investigated the intermediate-spreading Southeast Indian Ridge (SEIR) between Australia and Antarctica. A characteristic feature of this area is the Australia-Antarctic Discordance, an area of long-term, low magmatic budget on the ridge. We focus on the area east of the discordance, which displays prominent gravity highs on satellite-derived maps of the flanks of the SEIR between Tasmania and Antarctica. We show that these gravity highs likely correspond to volcanic seamounts and seamount chains, similar to those observed on the flanks of the East Pacific Rise. This area, in particular the volcanic chains, are associated with residual mantle Bouguer anomaly (RMBA) lows, suggesting thicker crust or hotter mantle or both under the study area. The large number of off-axis seamounts and the RMBA lows suggest an anomalously high magma supply under the southern flank of the SEIR, not only with respect to the magmatically-starved discordance area, but also with respect to regular sections of intermediate-spreading mid-ocean ridges. The volcanic chains are oblique to both the relative and absolute motions of the Antarctic and Australian plates. We suggest that the seamount chains might have formed above small-scale convective upwellings in the asthenospheric mantle close to the ridge axis, and that the obliquity of the ridges reflects a regional westward asthenospheric flow. This hypothesis is also supported by the intermediate-wavelength gravity lineations observed in the southern flank of the SEIR. The mantle flow at the origin of the magmatic anomaly appears to be partly dammed by the large transform faults.
The objective of the STORM (South Tasmania Ocean Ridge and Mantle) cruise proposal is to test this hypothesis. The cruise plan is to survey and sample the South East Indian Ridge axis between the eastern AAD (near 128°E) and the 140°E transform fault, and the off-axis volcanoes (especially between 136°E and 138°E). We plan to map the 140°E (George V) complex transform fault system, and to use wax coring to sample the ridge axis basalts and dredging to sample the off-axis seamounts and the transform fault system. In-situ measurements in the water column (nephelometry, and chemical sensors Fe/Mn/CH4 on CTD and wax cores) near the axis and in the transform faults will detect the presence of hydrothermal activity. The geophysical, petrological and geochemical results of the STORM cruise should allow to test the idea that the observed off-axis volcanism results from the partial melting of Pacific-type mantle as it flows from the southeast to the northwest. They should also provide constraints on how this regional flow from Pacific to Indian domains relates to the Balleny hotspot and the interaction of mantle flow and continental margins.
These investigations are now developped in the framework of the InterRidge Working Group on Circum-Antarctic Ridges (CAR WG) created in 2012.
STORM cruise scientific party: A. Briais, C. Hémond, M. Benoit, C. Boulart, D. Brunelli, G. Ceuleneer, V. Chavagnac, A. Delacour, D. Graham, M. Grégoire, B. Hanan, M. Janin, M. Maia, A. Maillard, L. Menjot, S. Merkouriev, F. de Parseval, R. Prien, M. de St Blanquat, G. Ramillien, J. Whittaker.

Continuous enrichment culture using diluted hydrothermal fluid as medium: insights into sulfur and iron biogeochemical cycles, microbial actors, and mineral interactions in active deep-sea vent chimney of Guaymas Basin

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Hydrothermal vents host highly diverse microbial communities exhibiting various metabolisms including those involved in sulfur or iron biogeochemical cycles. In order to investigate these cycles in the Guaymas Basin hydrothermal field, a cultural approach using a gas-lift bioreactor was chosen. An enrichment culture was performed for 23 days at 85°C using a crushed sample of active flange as inoculum and diluted hydrothermal fluid as culture medium. Daily sampling provided time-series record of active microbial diversity and medium geochemical composition, including sulfate, hydrogen sulfide and organic acids concentrations. Bacteria were shown to be dominant relative to Archaea during the whole duration of the culture with sequences affiliated to Epsilonproteobacteria (Sulfurimonas and Sulfurospirillum species), Betaproteobacteria (Ralstonia and Lepthotrix species), Gammaproteobacteria (Marinobacterium and Idiomarina species), Parvibaculum sp. and Microbacterium sp.. Archaeal sequences affiliated to Thermococcales, Archeoglobus sp., Geoglobus sp. and Ferroglobus sp., known to be involved in sulfur or iron cycle, were present during the whole cultivation time. Continuous measurement of medium chemistry and pH also allowed to evaluate the influence of medium composition on mineral-fluid interactions on microbial diversity. We show that microbial community structure are impacted by environmental condition changes such as pH variation that affects mineral phase dissolution and fluid composition which itself affect terminal electron donors/acceptors involved in microbial process. The differences in term of microbial diversity between the raw flange sample (i.e. in-situ), suspended culture in bioreactor and the flange sample at the end of the culture also reveal that continuous enrichment methods allow to access new communities and metabolisms that were not active in the original sample. All together, those results highlight that sulfur and iron biogeochemical cycles are important in hydrothermal system and highly dependent on the availability of dissolved sulfur and iron species and minerals that could be used by microorganisms.

Axial valley bounding faults and the exhumation of mantle-derived rocks at slow spreading ridges

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In a 1978 paper entitled « Necking of the lithosphere and the mechanics of slowly accreting plate boundaries » Jean Francheteau and his co-author Paul Tapponnier pioneered modern studies at slow spreading ridges by emphasizing the role of a pluri-kilometer-thick axial lithosphere subjected to plate divergence. This remarkable paper will be the starting point of my presentation. I will show how the most recent concepts in terms of axial faulting, ridge segmentation, and the widespread exhumation of mantle-derived rocks at slow and ultra-slow ridges are indeed built upon the (inferred or observed) characteristics of the axial lithosphere : its variable thickness, and its rheology. I will also illustrate the role played by complex and time variable interplays between magmatic, tectonic and hydrothermal processes to control these lithospheric characteristics.

When did Plate Tectonics start?

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Nous savons que la lithosphère continentale a été crée entre- 4 et -2,5 Milliards d'années. Elle fut sans doute créée à partir d'un matériel basaltique qui a largement recouvert la terre durant la période Hadéenne. Il est cependant intéressant de regarder quel était le comportement de la néo lithosphère continentale à l'Archéen. La Tectonique des plaques nous a appris que toute la structuration des domaines continentaux se fait aux limites des ensembles lithosphériques rigides et notamment aux limites entre océans-continents. On défend l'idée que ce ne fut pas toujours le cas et que les forces de volume furent dominantes durant l'Archéen et que donc il n'y avait pas de lithosphère au sens mécanique du terme durant le premier tiers de l'histoire de la Terre.

We know that the continental lithosphere has been created between 4 and 2.5 BY. This was done by recycling of basaltic material that was covering the main part of the Earth during Hadean time. We consider the behavior of the neolithosphere during Archean. If the actual plate tectonic model shows that the deformation of continental and oceanic material occurs at the boundary of lithospheric units and mainly at the ocean-continents boundaries, it was not always the case. We assume that body forces were prevalent before -2.5 BY instead of boundary forces and no lithosphere existed in a mechanical sense during the first third of the Earth history.

Microbial diversity of marine sediments from the Canterbury Basin, New Zealand (IODP Leg 317)

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Studies on the microbial communities of deep subsurface sediments have indicated the presence of Prokaryotes and Eukaryotes throughout the sediment column. A high-throughput 454-pyrosequencing approach combined to total cell counts and Q-PCR analysis of 16/18S rDNA, JS1-Chloroflexi , Crenarchaeaota, Geobacteriaceae and functional genes were performed to examine the microbial prokaryotic and eukaryotic diversity of a very deep sediment core (more than 1900 m long, 344 bathymetry) within the Canterbury basin.

Cells counts were generally low all along the core and of about 3,3 x 10^4 cells.cm^3 within the deepest sample (1922 mbsf; meters below the seafloor). Q-PCR analysis showed that Bacteria are more abundant than Archaea at great depths and that Eukarya are quantifiable down to at least 650 mbsf. Pyrosequencing data of the hypervariable regions of the 16S rDNA for Bacteria and Archaea showed that the prokaryotic diversity is changing drastically with depth. Shallow depths were dominated by Chloroflexi, Planctomycetes and the division OP9 for Bacteria and mainly by MCG (Miscellaneous Crenarchaeotic Group) and MBG-B (Marine Benthic Group B) for Archaea. Depths below 1400 mbsf were dominated by Alpha-, Betaproteobacteria, Acidobacteria and Firmicutes for Bacteria. Surprisingly, the domain Archaea was not detected at all below 650 mbsf in Q-PCR and pyrosequencing surveys. Pyrosequencing data of the 18S rDNA region showed that fungi are the most consistently detected eukaryotes in the marine sedimentary shallow and deep subsurface within the Canterbury basin.

Attempts in cultivating deep marine thermophiles were also performed and positive prokaryotic enrichment cultures were obtained on several samples collected at more than 1800 mbsf, indicating that these deep communities are active. Our results allowed us to extend previous lower life limits for (i) Bacteria, from 518 to 1922 mbsf and (ii) from less than 50 mbsf to 1740 mbsf for Eukarya and fungi.

Submarine and aerial inflated lava flows

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The PARISUB cruise was led in 2010 using the R/V L'Atalante, the Autonomous Underwater Vehicle (AUV) AsterX and the manned submersible Nautile (Ifremer). The goal is to investigate the processes that occur during the interaction between the Mathematicians hotspot and the East-Pacific Rise at 16°N. The present spreading axis has an elevation of at least 400m above the average depth of the North Pacific ridge, indicating a high magmatic production. Near-bottom high-resolution bathymetry is used to individualize and measure volcanic flows.

We identify remarkable smooth (at the scale of the high-resolution bathymetry) lava flows areas with surfaces ranging 0.2 to at least 1.5 km2, and thicknesses of few meters to 17 meters. These flows are primary composed of jumbled flows with occurrences of sheet flows, and minor occurrence of pillows on flow boundaries. Levees are observed at flow boundaries, which are characterized by a lobate shape of their edges. Cracks or clefts are observed at the flow's margins, likely paralleling the edge of the flow. Flows display a flat or slightly depressed surface, likely due the lava drained off from underneath when continuing to propagate. These flows emplaced on sub-horizontal floor. By analogy with subaerial features, we infer these flow were formed by the process of lava flow inflation. Flow inflation occurs in tube-fed lava flows when lava continues to be supplied to the interior of a flow that has ceased advancing, thus uplifting the flow's rigid surface. Terrestrial analogs are observed in Iceland, Hawaii, and in United States, Oregon, Idaho and Nouveau Mexique. The common point of all these lava flows is that they emplaced either in lacustrine environments (ex. Jordan Crater lava flows, Idaho, or Lake Mytvan, Iceland), in river beds (ex. Laki Flows, Iceland, or Owyhee River Flows, Idaho) and at the coast the below the sea level (ex. Budahraun lava flows in Snaefellness , Iceland).

Geochemical and morphological diversity of vent deposits from the Lau Back-arc Basin arising from variations in igneous rock composition and volcanic arc influence

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The Eastern Lau Spreading Center and Valu Fa Ridge of the Lau back-arc Basin trend obliquely to the Tonga-Kermadec active subduction zone. Variations in basement lithology, from basalt in the north to andesite, dacite, and rhyolite in the south, and localized influence of subduction zone components (e.g. addition of magmatic volatiles to hydrothermal fluids) lead to a diversity of vent deposit mineralogy, morphology, and geochemistry.

At the basalt-hosted Kilo Moana and TowCam vent fields, vent deposits are associated with fissures that cross-cut basaltic domes (Ferrini et al., 2008, G-cubed 9). High temperature (to 333°C) fluid exits from chalcopyrite-lined, zinc sulfide-rich branched chimneys and active spires. Deposits lack barite.

Further to the south, vent deposits at the Tahi Moana and ABE vent fields are morphologically and compositionally intermediate between those of basalt-hosted systems to the north and the more felsic-hosted systems to the south. Deposits are associated with normal faulting and include open conduit chimneys, flanges, and active spires. Greater proportions of zinc- over copper-iron sulfides are observed relative to the basalt-hosted counterparts. Barite is present on outer edges of deposits, and within flanges, but is less common at the more northerly Tahi Moana vent field.

The southern Tui Malila, Mariner, and Vai Lili vent fields, located on the Valu Fa Ridge, are associated with a range of basalts, dacites, and rhyolites. The felsic influence is reflected by higher proportions of Ba, As, and Pb in the deposits and an increased presence of barite-dominated flanges or squat edifices. Another distinguishing feature of these deposits is their close association with volcanic craters (Ferrini et al. 2008). While evidence for the influence of magmatic volatiles is absent at the Tui Malila vent field, it is present at the Mariner vent field, where high-temperature, low pH fluids (Mottl et al. 2011, GCA 75:1,013?1,038) form copper-rich, zinc-poor deposits, despite a high concentration of zinc in hydrothermal fluids (C.G. Wheat, unpublished data).

In contrast, active vent deposits sampled in 2005 from the Vai Lili vent field are indicative of waning hydrothermal activity (with maximum measured temperatures of 121°C). Older deposits are geochemically similar to those of the Mariner vent field, consistent with Vai Lili vent field being more active in the past, with past fluids similar in composition to those at the Mariner vent field (Fouquet et al., 1991, Nature 349:778?781; Mottl et al., 2011).

A detailed north-to-south overview of the mineralogy and geochemistry of vent deposit samples collected from these vent fields in 2005 and 2009 (based on reflected and transmitted light microscopy and bulk geochemical analyses), in conjunction with detailed bathymetric data (Ferrini et al., 2008) and vent fluid compositions (Mottl et al., 2011) documents connections between vent deposit mineralogy, morphology, and geochemistry and systematic trends in geologic setting and underlying lithology.

Earthquake precursors and super-critical fluids at oceanic fracture zones

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The seismicity of oceanic fracture zones has been the subject of debate over the last three decades. Early work suggested that ocean transform earthquakes display anomalously large excitation of long period waves [Kanamori and Stewart, 1976; Okal and Stewart, 1982], that could be explained by episodes of slow, smooth deformation, several hundreds seconds before the high frequency origin time [Ihmlé and Jordan, 1994]. The possibility of anomalously slow rupture preceding the normal speed rupture could be useful for short-term prediction. However, Abercrombie and Ekström [2001, 2003] have shown that errors and approximations in the centroid depth, focal mechanism, and earth structure at the source may have significant effects on the shape of the source spectra. Hence, the previously proposed slow rupture components could be simply explained as artifacts generated by the modeling procedure.

Still, the debate has been re-opened in the last decade, as hydroacoustic data recorded by hydrophones moored in the SOFAR channel have revealed that the seismicity at oceanic fracture zones exhibit specific characteristics compared to that at continental transform faults [Mc Guire et al., 2005]. A paramount example is given by the sequence of 72 hydro-acoustic, clustered events recorded 12 hours prior to the Mw 6.2 earthquake that occurred within the Blanco FZ, near the ridge-transform intersection on June 2nd, 2000 [Dziak et al., 2003]. In the latter case, the hydrothermal fluids circulating within the fault zone are likely to be under super-critical conditions. Super-critical fluids are characterized by high compressibility, comparable to the one of gas, and high density, comparable to that of water. The presence of gas or highly compressible fluids reducing the Skempton's coefficient to ~ 0 is known to delay the occurrence of rupture, and to increase the shear stress at which the rupture occurs [Maury et al., 2011]. When gas disappears, an instability point is reached in the stress path. The later this disappearance, the smaller the normal stress and shear increase to reach the failure criterion and obtain rupture. Hence, we here propose a water circulation related scheme that could explain the sequence of precursors observed at Blanco FZ, considering reasonable estimates for the hydro-geological characteristics of the crust. The model assumes that fault material dilatancy prior to the mainshock drives seawater flow, down to the earthquake nucleation zone. Immediately prior to the rupture, dilatancy tends to decrease. Due to the high compressibility of the saturating fluid, the effective stress increases, resulting in the fracturing of pre-existing crustal cracks, which allows the «gas » to escape and to originate the observed precursory events. The combination of the three following factors could explain why seismic precursors have so far been observed only in submarine environments : i) the presence of an infinite supply of water above the fracture zone; ii) the inter-connection between this reservoir and the earthquake nucleation zone ; and iii) the presence of super-critical conditions near the ridge transform intersection.

Current global plate motions: Shrinking plates & transform faults

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A central hypothesis or approximation of plate tectonics is that the plates are rigid, which implies that oceanic lithosphere does not contract horizontally as it cools (hereinafter «no contraction»). An alternative hypothesis is that vertically averaged tensional thermal stress in the competent lithosphere is fully relieved by horizontal thermal contraction (hereinafter «full contraction»). These two hypotheses predict different azimuths for transform faults. We build on prior predictions of horizontal thermal contraction of oceanic lithosphere as a function of age to predict the bias induced in transform-fault azimuths by full contraction for 140 azimuths of transform faults that are globally distributed between 15 plate pairs. Predicted bias increases with the length of adjacent segments of mid-ocean ridges and depends on whether the adjacent ridges are stepped, crenellated, or a combination of the two. All else being equal, the bias decreases with the length of a transform fault and modestly decreases with increasing spreading rate.

The value of the bias varies along a transform fault. To correct the observed transform-fault azimuths for the biases, we average the predicted values over the insonified portions of each transform fault. We find the bias to be as large as 2.5°, but more typically ? 1.0°. We test whether correcting for the predicted biases improves the fit to plate motion data. To do so, we determine the sum-squared normalized misfit for various values of gamma, which we define to be the fractional multiple of bias predicted for full contraction: gamma = 1 corresponds to the full contraction, while gamma = 0 corresponds to no contraction. We find that the minimum in sum-squared normalized misfit is obtained for gamma = 0.9 ±0.4 (95% confidence limit), which excludes the hypothesis of no contraction, but is consistent with the hypothesis of full contraction. Application of the correction reduces but does not eliminate the longstanding misfit between the azimuth of the Kane transform fault with respect to those of the other North America-Nubia transform faults. We conclude that significant ridge-parallel horizontal thermal contraction occurs in young oceanic lithosphere and that it is accommodated by widening of transform-fault valleys, which causes biases in transform-fault azimuths up to 2.5°.

Multi-agent modelling of Earth's dynamics

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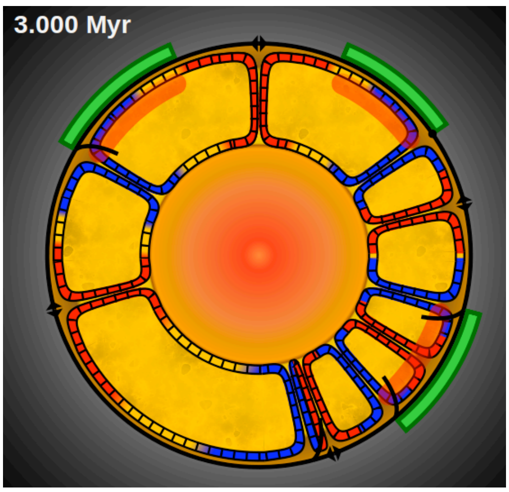
MACMA (Multi-Agent Convective MAntle) is a new tool developed at Laboratoire Domaines Océaniques (UMR CNRS 6538) and CERV (Centre Européen de Réalité Virturelle, LabSTICC, UMR CNRS 6285) to simulate plates tectonics and mantle convection in a 2-D cylindrical geometry (Combes et al., 2012). In this approach, ridges, subduction zones, continents and convective cells are agents, whose behavior is controlled by analytical and phenomenological laws. These agents are autonomous entities which collect information from their environment and interact with each other. The dynamics of the system is mainly based on a force balance on each plate, that accounts for slab pull, ridge push, bending dissipation and viscous convective drag. Insulating continents are accounted for. Tectonic processes such as trench migration, plate suturing or continental breakup are controlled by explicit parameterizations. A heat balance is used to compute Earth's thermal evolution as a function of seafloor age distribution.

We thereby obtain an evolutive system where the geometry and the number of tectonic plates are not imposed but emerge naturally from its dynamical history. Our approach has a very low computational cost and allows us to study the effect of a wide range of input parameters on the long-term thermal evolution of the system. MACMA can thus be seen as a 'plate tectonics virtual laboratory'. We can test not only the effect of input parameters, such as mantle initial temperature and viscosity, initial plate tectonics configuration, number and geometry of continents etc., but also study the effect of the analytical and empirical rules that we are using to describe the system. These rules can be changed at any time, and MACMA is an evolutive model that can easily integrate new behavioral laws.

For Earth-like input parameters, MACMA yields plate velocities and heat-flux in good agreement with observations. The long-term thermal evolution of the Earth obtained with our model shows a slow monotonous decrease of mantle mean temperature, with a cooling rate of around 50-100 K per billion years, which is in good agreement with petrological and geochemical constraints. Heat flux and plate velocities show a more irregular evolution, because tectonic events, such as a continental breakup, give rise to abrupt changes in Earth's surface dynamics and heat loss.

Combes, M., Grigné, C., Husson, L., Conrad, C.P., Le Yaouanq, S., Parenthoën, M., Tisseau, C. and J. Tisseau (2012), Multiagent simulation of evolutive plate tectonics applied to the thermal evolution of the Earth, Geochem. Geophys. Geosyst., Vol. 13, Number 5, doi: 10.1029/2011GC004014



Simulation environment for the MACMA Model

Ni isotope in ferromanganese crusts and deep-sea-clays: hydrogenetic and authigenic precipitation of Mn-oxides

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Modern deep-sea environments are particularly relevant to study transition-metal behaviors since they are enriched in metalliferous deposits such as ferromanganese crusts and manganese nodules, the latter being economically of interest. However processes that led to metal enrichment in Mn-nodules still remain unclear, in particular the contribution of each potential sources of metals during their formation, e.g. diagenetic, hydrogenetic, biologic or hydrothermal.

To help shedding light on this subject, we investigated Ni isotope systematics on these different marine deposits. Our results on bulk and microsampled layers Fe-Mn crusts (from Atlantic and Pacific ocean locations) indicate that (1) Ni isotope have systematically positive delta60/58Ni values up to +1.9 per mil which is very high compared to the value of +0.05 ±0.05 per mil determined for the Bulk Silicate Earth (BSE), (2) there is no variation in Ni isotope composition according to depth in the crust (i.e. age of the crust) even if geochemical variations do occur. It shows that Ni isotope composition of seawater remains fairly constant during crust formation, i.e. during more than 10 Myr, and more importantly it means that hydrogenetic Ni in modern oceans has a constant isotopic signature. In contrast, Ni isotopes in deep-sea clays show variations with depth of the sediment, which are correlated with increasing metal content in the sediment (i.e. Mn, Ni, Cu, Fe, Zn and Co) likely due to authigenic Mn-oxides precipitation. This compelling correlation between Mn-oxides precipitation (and Ni concentration) and increase in Ni isotope values from +0.04 per mil to +1.03 per mil probably indicates that Ni isotope composition of deep-sea-clays is the result of mixing between a BSE component (strictly deep-sea clays) and a component with a positive isotopic composition, probably dissolved Ni in sediment pore-waters that precipitated in Mn-oxides within the sediment.

Basalt alteration by endemic microorganisms of hydrothermal vents

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At and near mid-ocean ridges, an important hydrothermal circulation is created in the crust. The subsequent alteration involving hydration and oxidation reactions is theoretically capable of supplying energy for chemoautotrophic microbial growth, thriving on the sulphur, metals, nitrogen, hydrogen and carbon that are transported by the hydrothermal fluids. It has been previously shown that the oceanic lithosphere and in particular the basaltic component host a large diversity of microorganisms that could in turn be involved in the alteration processes. Nonetheless, the microorganisms/rock interactions are not completely understood and the mechanisms and their magnitude are still unclear mainly due to the difficulty to differentiate between biotic and abiotic alterations figures, and to attribute a microbiological origin to the alteration by-products. The aim of this work is to assess the role of microorganisms in the processes of basalt alteration, by distinguishing biotic alteration from abiotic alteration.

With this aim, microbial incubators containing synthetic MORB glasses (enriched either in oxidized iron, reduced iron or 57Fe isotope), have been deployed since 2006, at the Lucky Strike hydrothermal site (37°N, 32°W) in the framework of the MoMAR (Monitoring the Mid-Atlantic Ridge) project. During 6 French cruises, biotic and abiotic incubators have been deployed and recovered around different vents all around the Lucky Strike hydrothermal field, in a way that they allow comparison of the biodiversity and the associated level of alteration according to the incubators substrata, duration of in situ incubation and environmental parameters (Temperature, composition of surrounding fluids). Locations, from near-axis to off-axis, were selected for their variability in fluid influence and composition. The duration of the in situ incubation varies from only few weeks to more than two years. Once recovered, the nature and the level of the microbial colonization of each sample are characterized by pyrosequencing of the 16S RNAr, complemented with fluorescent in situ hybridization (FISH) experiments. In parallel, the basalt alteration is investigated at the appropriate microscale using Scanning, Transmission Electron Microscopies and Raman spectroscopy.

Preliminary results show highly variability in the degree of colonization and the obtained alteration phases, related to hydrothermal fluids influence. Nonetheless microbial cell occurrences appear to correlate with iron-bearing alteration phases that Raman spectral analysis define as different iron oxides: hematite, goethite, magnetite or mackinawite. This alteration phases could be linked to specific metabolisms like the iron-oxidizing Zetaprotebacteria affiliated to Mariprofondus ferroxidans, diverse sulphide-oxidizing bacteria (eg. Thioalkalivibrio) or iron-reducing bacteria (eg. Ferrimonas, Geobacter) as revealed by 16S RNAr sequences analysis. Moreover, comparison of the diversity and composition of microbial community in samples incubated near an active hydrothermal chimney or incubated in a sedimentary of axis environment, show that the compositions are deeply different and the diversity is really more important near active chimney. This could imply that hydrothermal fluid shape the composition and influence the diversity. Next step will focus on the study of the impact of the time fluctuating environmental conditions on the nature of the microbial communities and their involvement in the alteration processes.

Jean Francheteau & Seafloor Spreading Reorganizations: Microplates, Propagators, Overlappers, & Iceland

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Jean Francheteau was one of the most important marine geophysicists in the period immediately following the plate tectonic revolution, & was responsible for many major advances in understanding seafloor spreading patterns & plate boundary reorganizations. He was one of the first to map the distinctive overlapping spreading center «69» pattern along the fast-spreading EPR with Seabeam, & to realize these were small-scale propagators. He studied rift propagation on the large-scale at Hess Deep, where his regional Seabeam survey showed conclusively that the Cocos-Nazca ridge is propagating into EPR-spread crust at the evolving Galapagos triple junction, & on an even larger scale at the superfast-spreading EPR microplates. He was the first to use Seabeam to map parts of the Easter Microplate, & his more extensive mapping on that same expedition established the existence of the remarkably similar Juan Fernandez Microplate. His research has several important implications for new advances in understanding Iceland & how the Iceland hotspot interacts with the Mid-Atlantic Ridge.

The recent evolution of Iceland can now be understood in terms of 2 counter-rotating edge-driven microplates with dominant ridges (the Eastern & Northern Volcanic Zones) propagating in opposite directions from the hotspot, producing the Central Volcanic Zone along the predicted zone of extension between these microplates. South of Iceland, there is a major ongoing diachronous reorganization of North Atlantic seafloor spreading, from a previous orthogonal ridge/transform geometry to the present oblique spreading geometry without transform faults on the Reykjanes Ridge. This reorganization is usually interpreted as a thermal phenomenon, with a pulse of warmer mantle expanding away from an Iceland plume causing a progressive change in subaxial mantle rheology from brittle to ductile, so that transform faults can no longer be maintained. Given that this is certainly the most obvious & arguably the type-example of active plate boundary reorganization, it is somewhat surprising that a thermal mechanism has near universal acceptance here whereas most if not all other seafloor spreading reorganizations are equally confidently thought to result from the tectonic rift propagation mechanism. One reason the propagating rift alternative was ignored here was that the V-shaped ridges, troughs & scarps (VSRs) enclosed by the reorganization wake had long been thought to be symmetric about the Reykjanes Ridge axis, & if this were true, rift propagation, which must produce asymmetric wakes, could not have occurred. However, we collected marine geophysical data that show the VSRs actually have an asymmetric geometry consistent with rift propagation, not with previous pulsing plume models, so they can no longer be considered obvious proof of a pulsing Iceland plume. Additionally, a significant new result (Benediktsdóttir et al., 2012, G-cubed) is that excellent magnetic anomaly fits can only be obtained if some rift propagation toward Iceland has also occurred. The propagation toward Iceland presumably could not be driven by plume pulses although propagation away from Iceland obviously could be. (An area of seafloor near the Azores hotspot, previously proposed to be analogous to the Reykjanes VSRs & to result from a pulsing Azores plume, also appears to show the kind of asymmetric accretion required by rift propagation). It may be that both processes are active, but if only one is required the evidence for rift propagation is stronger than for Iceland plume pulsation. Following Occam, the possibility should be considered that the troughs defining the V-shaped ridges form by propagating rift processes, such as transient near-zero spreading rates & the cold wall hydraulic head loss effect of rifted preexisting lithosphere, that on larger scales create deep propagator tip troughs such as Hess Deep & Pito Deep.

Pito Deep, named by Jean Francheteau after the original Polynesian name for Easter Island, Te pito o te henua, «the navel of the world»), is at the tip of the propagator that initiated the Easter Microplate, & is Earth's deepest axial valley. Hey had the great pleasure of sailing on the Nautile expedition Jean led to the Easter Microplate, focusing on Pito Deep. He was greatly impressed that French oceanographers were still treated as adults, unlike U.S. oceanographers, with seemingly bottomless carafes of red & white wine at every meal, & after that advised his students & colleagues to sail on French ships every chance they got.

The involvement of rift propagation in VSR formation suggests this is also a possible explanation for the ongoing major transform-fault eliminating Reykjanes Ridge reorganization. If so, the tip of the reorganization would presently be near the first transform fault south of Iceland, the Bight transform near 56.8N, rather than in the extensively surveyed area 200 km farther north where the thermal reorganization model predicted the reorganization tip should be. A 2013 expedition will test this hypothesis.

Although Jean never could explain quaternions simply enough that I could understand them, I will remember him as a fine scientist, good-natured friend, gracious host, & a pleasure to dine & sail with.

Thermal Structure and Stability of Thick Continental Lithosphere

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The lithospheric mantle beneath continents has been depleted through melt extraction, which makes it intrinsically buoyant with respect to the asthenosphere, but it is also cooled from above. The unstable thermal stratification may induce two very different types of convection. One develops in the asthenosphere over small time-scales and length-scales and is required to supply heat flux to the lithosphere. The other type of convection may affect the lithospheric mantle itself and is the most interesting one for geology because of its remarkable geometrical features. For a two-layer system involving constant viscosity fluids with different physical properties, dynamical behaviour depends on two dimensionless numbers, a Rayleigh number for the upper layer, Ra, and a buoyancy number, B, that scales the intrinsic density contrast, Drc, to the thermal one, DrT= a ro DT, where a is the coefficient of thermal expansion, ro a reference density and DT the temperature difference across the layers. The critical Rayleigh number for instability depends strongly on the buoyancy number, from about 28 at low values of B to 1100 for B ? 0.5. Two different types of convective motions can occur depending on the B value. For B 0.5, the upper layer undergoes internal convective overturn with little deformation of its base.

For a continent of finite width, this new type of convective instability leads to a remarkable spatial pattern at the scale of an entire continent. We have carried out fluid mechanics laboratory experiments on buoyant blocks of finite size. Within the block, instability develops in two different ways in an outer annulus and in an inner region. In the outer annulus, upwellings and downwellings take the form of radial rolls spaced regularly. In the interior region, the planform adopts the more familiar form of polygonal cells. Translated to geological conditions, such instabilities should manifest themselves as linear rifts striking at a right angle to the continent-ocean boundary and an array of domal uplifts, volcanic swells and basins in the continental interior. The laboratory data lead to simple scaling laws for the dimensions and spacings of the convective structures. For the sub-continental lithospheric mantle, these dimensions and distances take values in the 500-1000 km range.

We may link these convective features to geological structures. Domal uplifts, volcanism, basin formation and rifting have often struck the same continent in different areas at the same time. Their characteristics and orientations are difficult to reconcile with mantle convection or tectonic forces and suggest a driving mechanism that is intrinsic to the continent. The rifts seem to develop preferentially at high angles to the edge of the continent whereas swells and basins seem confined to the interior. Another intriguing geometrical feature is that the rifts often branch out in complicated patterns at their landward end.

In Western Africa, for example, magmatic activity currently occurs in a number of uplifted areas including the peculiar Cameroon Volcanic Line that stretches away from the continental margin over about 1000 km. Magmatic and volcanic activity has been sustained along this Line for 70 My with no age progression. The mantle upwelling that feeds the volcanoes is not affected by absolute plate motions and hence is attached to the continent. The Cameroon Volcanic Line extends to the Biu swell to the North and the Jos plateau to the west defining a striking Y-shaped pattern. This structure segues into several volcanic domes including the Air, the Hoggar, the Darfur, the Tibesti and the Haruj domes towards the Mediterranean coast. Another example is provided by North America, where the late Proterozoic-early Ordovician saw the formation of four major basins, the Michigan, Illinois, Williston and Hudson Bay, as well as of major rifts in southern Oklahoma and the Mississippi Valley within a short time interval. There was also a series of swells/uplifts at the same time, such as the Ozark and Nashville domes.

These geological structures follow the spatial pattern of convective instabilities and their spacings and dimensions are within the predicted range. The large intrinsic buoyancy of Archean lithospheric roots prevents this type of instability, which explains why the widespread volcanic activity that currently affects Western Africa is confined to post-Archean domains.

Ophiolites and oceanic crust : the permanent dialog

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Since the Penrose Conference about Ophiolites in 1972, a permanent dialog was instored between marine geoscientists working on the oceanic crust, and geologists working on land on the ophiolite complexes, in the mountain ranges of the world.

Any discovery, any new model in one field had immediate repercussions in the other one. Models on the structure and composition of the oceanic crust were first strongly influenced by the ophiolite data and models (Troodos, Oman...), for the simple reason that oceanic data were scarce, especially concerning the deep parts of the crust. Ophiolites offered during a long time the undisputed advantage of presenting complete sections of fossil oceanic crust and transition to the upper mantle.

In a first time, purely magmatic models, with reference to the so-called "Penrose Conference" model, were proposed to describe the lithological organization of the oceanic crust and to match the seismic data. However, year after year, tremendous efforts of the oceanic community brought up a lot of samples and data, which obliged to reconsider many well-established models. In particular, drilling and exploring the ocean crust by submersible revealed the importance of tectonic and hydrothermal processes in the genesis of the oceanic crust, especially in slow-spreading oceans.

On the other hand, continued progresses in mapping and studying ophiolites lead to the conclusion that most of them were not created at oceanic ridges, but rather in SSZ (Supra Subduction Zone) environments. The classification of ophiolites in HOT (Harzburgite Ophiolite Type) and LOT (Lherzolite Ophiolite Type) types, supposed to represent fossil fast- and slow-spreading oceanic ridges respectively, had to be completed and revised.

I shall present several examples showing how the modeling of the structure of the oceanic crust, of the oceanic accretion magma chambers, or of the oceanic hydrothermal circulation systems, has been permanently improved by both sources of data.

In conclusion, our comprehension of the magmatic, tectonic and hydrothermal processes controlling the building of the oceanic crust has widely benefited from crossed information of data and models, permanently issued from both "on land" and «under sea» oceanic fields.

From Paleomagnetism to Plate Tectonics, the contribution of Jean Francheteau to the discovery of finite Plate Tectonics

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Plate tectonics provides a kinematic model that explains the tectonic and seismic activity now occurring within the upper layer of the earth as resulting from the interaction of a small number of large rigid plates whose boundaries are the seismic belts of the world. But the only seismicity we know is the contemporaneous seismicity. Thus strictly speaking the model can only be applied to describe the present instantaneous kinematics. How legitimate is it to extrapolate it to the past to reconstruct the history of the Earth moving from physics to geology? What are the uncertainties involved in this extrapolation? These were major questions when plate tectonics burst within the Earth Sciences forty-five years ago. Most the early pioneers only progressively moved from instantaneous present plate kinematics to past finite kinematics. But Jean Francheteau who arrived at Scripps to work on heat flow measurements, moved rapidly to finite past kinematics as soon as he heard about the new model, testing the stability of finite plate rotations through a study of the trends of the Pacific fracture zones and then devoting his entire PhD thesis in 1968 to « Paleomagnetism and Plate Tectonics». His rigorous quantitative approach taking into account as much as possible the uncertainties was a pioneering work in the early stages of Plate Tectonics. Thus when Jean Francheteau arrived in the CNEXO laboratory that I was then heading in 1971 and started working with Jean Bonnin on our book Plate Tectonics, we soon confronted our two approaches from the past to the present for Jean Francheteau and from the present to the past for me. This allowed us to propose the first integrated complete vision of plate kinematics in our book, Jean Francheteau covering most of finite tectonics and paleomagnetism in the chapter « Movements related to a frame external to plates» while I covered most of the instantaneous kinematics. In a sense I feel that this confrontation is still essential for a correct approach to Plate Tectonics.

Lava flows morphologies at the East-Pacific Rise at is intersection with the Mathematician hot-spot, 16°N

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The PARISUB French cruise in 2010 on board the Atalante, used the Autonomous Underwater Vehicle (AUV) Aster-X and the manned submersible Nautile (Ifremer). Surface geophysical data (multibeam bathymetry, magnetism, gravity) and near bottom data (high-resolution bathymetry, magnetism, plume mapping) were collected in order to investigate in detail the mechanisms of the interaction between the Mathematicians hotspot and the East Pacific Rise (EPR) at 16°N.
We use high-resolution (2 m) bathymetric data acquired by AUV during the cruise to map tectonic and volcanic structures: faults, fissures, mounds, collapsed lava lakes, lava flows etc., and to identify individual volcanic deposits. We use Nautile dive videos and photos to inform our interpretation of the bathymetric data. Then it is possible to associate lava flow morphologies (e.g., pillows, lobate flows, sheet flows) to the bathymetric morphology and roughness so that we may develop a morphology map over the entire bathymetric data set. The EPR around 16°N has a spreading rate of 85 mm/an, the observations have shown that lobate flows predominate over sheet flows, and pillow flows are also well-represented.
We identified remarkable smooth lava flows on both sides of the axial graben that we interpret to be analogs to subaerial inflated flows. Their surface area reaches 9 km² and their thickness a few meters to 10 m. They are primarily composed of jumbled and smooth sheet flows. Steep levees with cracks at their summit are observed at the flow boundaries., The upper surfaces of the flows are flat or slightly depressed , likely due to the lava draining from underneath during emplacement. These flow structures as well as a tumulus observed around 15°43,5'N are comparable to those described for inflated flows in Hawaii and Iceland and W. North America. We hypothesize that low eruption rates and very small seafloor gradients are responsible for their development.

The life cycle of back-arc basins: an experimental approach

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Series of analog centrifuge experiments, complimented by analytic modeling, shed intriguing light on the significance of tectonic friction as a key parameter in the array of tectonic processes that constrain the birth of back-arc basins, their maturity and their extinction.

The experiments suggest that the initial stages of subduction are linked with the swing of the ocean-continent lithospheric contact zone from dipping seawards to be directed landwards, until, at a shallow dip, its gradient enables displacement, and the initiation of the motion and its rate of offset depend on lithospheric friction. The analytic model suggests that no motion takes place along the contact zone between the oceanic and continental lithospheres as it swings up to its critical landwards slope. The experiments show further that friction determines both the rate of the subduction of the underthrust slab and the style of deformation of the overlying lithosphere (Mart et al., 2005). Extensional faulting in the hangingwall block constrains, in turn, the diapiric ascent of upper mantle material, and the possible rifting of the back-arc basin. This process takes place already when the lighter lithosphere is driven underneath the denser one, so that it explains not only the ocean-continent subduction but the ocean-ocean subduction as well. When the denser lithosphere is driven below the lighter one to depths exceeding 60 km, eclogitization increases the density of the down-going slab above the that of the asthenosphere, and the down-going slab drives its way into the mantle. There is ground to presume that a critical factor that controls the friction in subduction is the generation of serpentinite, which depends on the availability of water in the deep crust, which is derived from the metamorphism of amphiboles and micas. The soft serpentinitic minerals lubricate the contact zone between the moving slabs and reduce the friction between them. Furthermore, the diapiric ascent of the serpentinites increases the density of the downgoing slab and enhances its subduction.

A second series of centrifuge experiments studied subduction constraints of back-arc basins, presuming that while the subduction of oceanic lithospheres could be constrained by unknown primordial parameters, back-arc basin subduction definitely post-dates its crustal accretion. The reported experiments drove the back-arc lithosphere underneath the island arc, pulling behind it the brittle continental lithosphere, so that the floor of the back-arc basin was totally subducted under the island arc, but the continental and the island arc crusts collided, forming a series of folded structures. Dewey (2005) suggested that the time of the back arc cycle, from its early supra-subduction to its mountain building stage could be less than 20 Ma.

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Drilling the ocean lithosphere

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Scientific ocean drilling was initiated in the late sixties with the ambitious aim of drilling the crust/mantle boundary, the MOHO, The technology was not there, and this first attempt was abandoned. However, it lead the way to the initiation of the very successful successive ocean drilling programs, DSDP, ODP and IODP. Drilling the ocean lithosphere has been a constant goal of these programs. Although drilling into hard rocks remains a technological challenge, major progress in the understanding of lithosphere generation at mid-ocean ridges and evolution with time has been accomplished. By providing direct access to the third dimension, drilling is definitively a key complement to geophysical approaches as well as investigations at the seafloor.

Knowledge about the construction and alteration of the upper crust immensely benefited from a number of holes drilled in the Atlantic, and mostly from the now famous Hole 504B drilled in the young crust generated at the Costa Rica rift. More recently, Hole 1256D located in the Eastern Pacific accomplished another major step by reaching the dike/gabbro transition. Characterization of the pattern of seawater circulation and associated reactions and geochemical fluxes is among the major results obtained in these holes. The role of bacteria in the alteration of the ocean crust was clearly evidenced and opened new avenues of research.

While drilling the upper crust slowly progressed, Hole 735B located at the South West Indian Ridge drilled directly into outcropping gabbros in 1987. It provided a completely new view of the lower crust generated at ultraslow spreading ridges by stressing the interplay between magmatic, tectonic and hydrothermal activity. As a result, the concept of «offset drilling» was developed. The idea was to take advantage of so-called «tectonic windows» and drill directly into outcropping lower levels of the lithosphere. Drilling peridotites and gabbros at Hess Deep (Pacific crust) and MARK (Atlantic crust) contributed to stress the differences between the lithosphere generated at fast and slow spreading ridges respectively. More holes were drilled into gabbros and peridotites at the Mid-Atlantic Ridge as the concept of heterogeneous crust and detachment faulting emerged. They contributed to a better understanding of the construction of the lower crust and of serpentinization processes and their role in geochemical fluxes. The failed attempt to reach in situ mantle rocks at Atlantis massif (30°N) proved the difficulty of interpreting geophysical data and emphasized the need for groundtruthing indirect measurements. However, an extremely valuable gabbroic sequence was recovered.

The current phase of IODP is ending in September 2013. For the next phase, the international community has elaborated a new science plan. Ocean lithosphere remains a major target for future drilling. A better understanding of detachment faulting, the role of biogenic activity in alteration processes, and evaluation of the feasibility of carbon sequestration in the ocean lithosphere are among the new priorities. But the most challenging goal remains drilling through the MOHO into the pristine Earth mantle.

Jean Francheteau and Reconstructing Plate Motions

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I first got to know Jean in the summer of 1969 while I was a visiting scientist at Scripps and he was concluding his thesis work. Very fortunately for me, he sent me a copy of his thesis the following year. In the opening section of his thesis he discusses how to add finite rotations in 3-D and has illustrations of constructions used to prove "Rodrigues' Theorem #1" (graphically how to find the pole of the single rotation resulting from 'adding' two rotations) and "Rodrigues' Theorem #2" (how to find the resulting angle of rotation about this pole). [The same illustrations and an expanded discussion are in the 1973 book by Le Pichon, Francheteau, and Bonnin.] These 'theorems' are based on the paper by Olinde Rodrigues that appeared inJournal de Mathématiquesin 1840. Rodrigues's paper did not show these constructions, in fact it had no figures at all ? Jean said he learned the constructions while a student at Nancy. I of course knew that the process of combining finite rotations was non-commutative (i.e., first rotate 'A', then rotate 'B' does not give that same result as first 'B', then 'A' ? in matrix terms B A ? A B), but for me this was just a purely mechanical, matrix-multiplication sort of understanding. There was a widely known example of a book rotated first about a vertical axis, then a horizontal axis andvice versa(first the horizontal axis, then the vertical) used to illustrate the non-commutative nature of finite rotation operations; but Jean's introduction of the Rodrigues constructions into the geophysics community gave a deeper, intuitive sense of what finite rotations were all about beyond just matrix manipulation. In making a 'string' of several finite rotation operations to describe plate motions or hotspot tracks, it becomes very important to arrange them in the proper order. While at Brest in 1973 I had many discussions with Jean about this problem and worked to develop an 'algebra' to determine the correct order of rotations needed to obtain a desired result. In my talk I shall illustrate some of the key points of this algebra.

Seamount Morphology and Structure of the Southwest Indian Ridge (40°E-60°E)

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The South-West Indian Ridge (SWIR) between longitude 40°E and 60°E is an ultraslow spreading (~16 mm/a) mid-ocean ridge system with a highly oblique (>50°) spreading direction and a large number of closely spaced transform faults. Previous swath bathymetry surveys onboard R/VDr. Fridtjof Nansenin 2009 show that the ridge crest is characterised by a number of irregularly shaped seamounts which rise about 2500 m above the mean depth of the surrounding seafloor. In November/December, 2011 we re-surveyed 5 of these seamounts onboard RRSJames Cookusing an EM120 swath bathymetry system, a Lacoste-Romberg air-sea gravimeter and a Remotely Operated Vehicle (ROV). Preliminary results show that the seamounts are highly fractured, with fault trends parallel and orthogonal to the spreading direction. There is evidence of both growth and collapse structures, including head scars, chutes and debris flows. We present here a preliminary analysis of the morphology and its implications for mass wasting and eruptive processes at young seamounts that have formed in an active extensional setting. In addition, shipboard gravity data was compared with synthetic profiles to determine the flexure due to loading of the seamounts, and therefore the elastic thickness of the plate. This along with large scale Mantle Bouguer anomalies were used to make inferences about the deep ridge structure and along ridge variation.

T-waves: Guardians of hidden ocean processes

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Jean Francheteau spent his professional life exploring the mysteries of the ocean floor, hidden from direct exploration by an average of 4 km of water. In this respect, the exceptional efficiency of the propagation of T phases in the SOFAR channel provides a unique tool for the investigation of physical processes generated in the oceanic column or as a result of its coupling with the solid Earth. After a brief historical review, we will describe a number of recent developments in the study of T waves. These include (i) the definition of the ratio of T-phase energy flux to seismic moment as a quantitative estimator of the slowness of seismic sources, allowing the robust identification of slow events such as "tsunami earthquakes"; (ii) the development of criteria for the effective discrimination of explosionsand earthquakes in the marine environment; (iii) the identification of underwater volcanic processes in remote areas such as the Southern part of the Pacific Basin; and (iv) the investigation of "ice symphonies" detectable at teleseismic distances, generated by stick-and-slip processes during episodes of collisions between mega-icebergs calved from the Antarctic ice shelf.

Mid-Ocean Ridge Volcanism on the East Pacific Rise: Integrated Volcanological, Geophysical and Geochemical Studies

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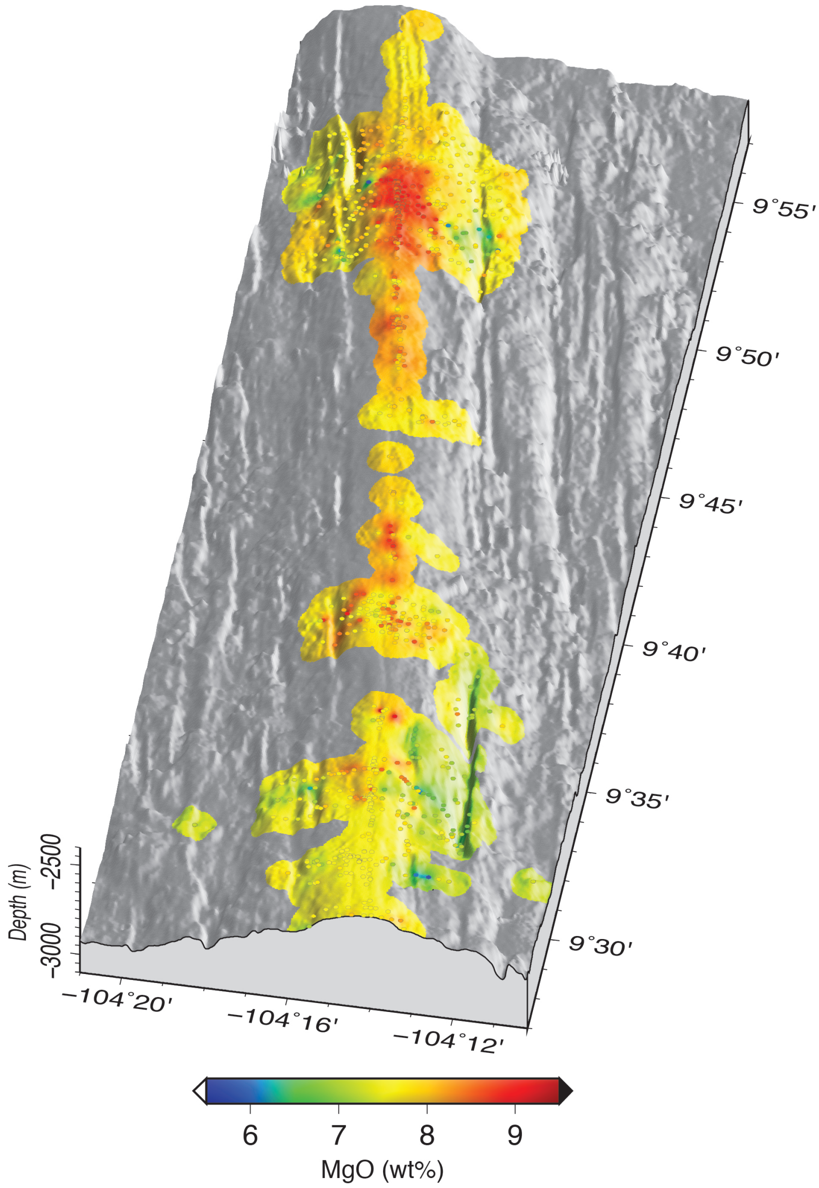
Since 1991, the 9°-10° N section of the East Pacific Rise (EPR) has been intensively studied during 18 cruises, which utilized Alvin, the Jason 2 ROV, camera tow, side-scan sonar, rock coring and dredging. The crust and upper mantle of this section of the EPR has been extensively studied using multichannel seismic techniques. The 9° 50' area is unique in that it has erupted twice since our investigations began in 1989. Much of the research has focused on recent eruptive events in the axial summit trough (AST), the small overlapping spreading center (OSC) at 9°37' N, the off-axis crestal plateau out to about 4 km (80 kA) from the axis and the large OSC at ~9° N. Nearly 1500 lava samples from this ~ 960 km2 area have been recovered and chemically analyzed providing the most comprehensive data set available to determine the history of magmatism and crustal accretion along any ridge crest. Detailed sampling, mapping, and analysis of the physical volcanology of the different lava terrains have yielded estimates of eruption volumes, effusion rates, eruption frequency and a surprising amount of chemical heterogeneity along this fast spreading ridge segment. Our extensive and detailed geochemical studies at the EPR highlight how a thorough understanding of the variability in lava compositions on small spatial scales (i.e., between lava flows) and large scales (i.e., from segment center to segment end) can be used in combination with seafloor photography, lava morphology, bathymetry and geophysical data to provide insights into the magmatic system that drives volcanism and influences hydrothermal chemistry and biology at a fast-spreading MOR.

Overall, the observed major element chemical variations in MORB from the EPR can largely be explained by shallow-level crystal fractionation in the oceanic crust. However, trace element and radiogenic isotopic variations require variable sources and extents of melting in the sub-ridge mantle. Additionally, the distribution of the different basalt types is not symmetric across the crestal plateau. This is due partly to off-axis eruptions and additionally is a consequence of the asymmetric way in which lava flows away from eruptive fissures at the axis, often determined by meter-high variations between opposing rims of the AST. Results of our geochemical investigations show that the most recent magmatic events associated with the present AST (within ~500 m of the axis) erupted relatively homogeneous and mafic (>7.5 wt.% MgO) normal mid-ocean ridge basalt (N-MORB) characterized by having very low abundances in the most incompatible trace elements such as barium, uranium and potassium (e.g. K2O/TiO2 x 100 13) on the flanks of the crestal plateau and commonly associated with fault scarps and fissures. The range of MORB trace element and isotopic compositions suggests that there are at least 2 or 3 distinct mantle sources from which the basaltic melts were derived. The only E-MORB recovered on-axis were recovered at the OSC at 9° 37'N and 9°N, suggesting that the various basalt magma « genotypes» that feed the ridge crest are not efficiently mixed under ridge discontinuities where seismically imaged axial magma chambers (AMC) are segmented. While it is probable that axial basalts have erupted directly from the AMC, there must also be compositionally distinct pockets of cool, unmixed melts in the margins of the AMC or from separate segments along strike where the magma lens thins along axis. Although the general observed chemical variations in N-MORB are largely controlled by cooling and crystallization of melts at shallow crustal levels, data from gabbroic xenoliths entrained in some lavas also indicate that melt mixing and reaction with preexisting crystals occurs at depth.

The relative homogeneity of MORB compared to other tectonic settings is commonly attributed frequent recharge of axial magma chambers with more primitive, less evolved melts. However, as noted at other ridge segment discontinuities, we recovered a remarkable diversity of lava types ranging from ferrobasalt to highly evolved andesites and dacites along the western, propagating limb of the 9°N OSC. The formation of these SiO2-rich lavas requires a combination of extensive fractional crystallization and assimilation of the altered ocean crust in an environment where basaltic magmas can undergo extensive cooling and crystallization without repeated magma recharge. Our well-constrained petrologic data sets from the northern EPR provide a clearer picture of the various MOR magmatic processes that start with melting in the mantle and ultimately end with eruption of basalt on the seafloor. Our findings indicate that compositions of magmas erupted at fast-spreading ridges integrate a variety of processes that modify the compositions of melts as they ascend from the underlying mantle, which is in itself heterogeneous. Melts with different compositions are likely stored within the shallow melt lenses located at ~ 1.5 km below the seafloor which act as catchments for magmas that percolate through the oceanic crust. Within these reservoirs, magmas are homogenized and cooled to variable extents allowing them to differentiate along specific compositional trends. Our fine-scale sampling and mapping studies have shown that the compositions of most MORB reflect a myriad of processes dominated by mixing and fractional crystallization of mantle melts that occur over very short time scales (decades). The eruptions that deliver those melts to the seafloor and the resulting lava flows often can result in significant variations in chemistry between adjacent lobes of lava on small spatial scales (< 100 m to a few kilometers).



Spatial variation of MgO content of lavas collected from the northern East Pacific Rise overlain on the seafloor bathymetry. Colored dots represent the location of individual samples. Color gradations represent averaged distribution of MgO contents in lavas.
A contoured surface was calculated from the averaged values with variations in MgO content represented by color variation (see scale). The surface is overlain on a 3D gray-scale image of seafloor topography created from multibeam bathymetric data.

Crustal Accretion and Petro-geochemical Processes at Seafloor Spreading Ridges

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Over the past two decades technological advances have allowed us to map and sample the mid-ocean ridges (MOR) in great detail and to analyze lava samples with much greater speed and precision than ever before. Such investigations coupled with recent multichannel seismic studies of the oceanic crust and upper mantle have provided us with new paradigms of magmatic accretion at MOR. Two of the most thoroughly studied mid-ocean ridge segments include the East Pacific Rise (EPR) between 9°N and 10°N, and the southern Juan de Fuca Ridge (JdFR). Modern investigations utilize integrated multiple near-bottom vehicle systems including: Remotely Operated Vehicles (e.g. Jason 2, Tiburon, ROPOS), 120 kHz sidescan sonar, autonomous vehicles (ABE, Sentry), submersibles such as Alvin, and TowCam, a deep-towed digital camera system. Detailed maps and analysis of volcanic flow contacts, fissures and faults imaged by sidescan at ~2 m pixel resolution, coupled with in situ observations and photographic imagery provide data on flow types and thicknesses, fault throws, fissure depths, vent locations and sediment distribution. The chemical and petrologic characteristics of accurately located and well documented lava samples recovered in concert with these observational data have been successfully used to ascertain relationships between volcanic emplacement processes, hydrothermal venting, and the petro-geochemical processes responsible for crustal accretion.
Geochemical analysis of major, minor (including volatiles) and trace elements in mid-ocean ridge basalts (MORB) and crystals provide critical constraints on the various physical conditions and magmatic processes that may have been involved in the petrogenesis of individual flows. The interpretation of various element-element, ratio-ratio, and trace element normalized diagrams provides clues to the sources and processes involved. These include: fractional crystallization (deep and shallow), magma mixing, crustal assimilation, crystal-melt interactions (sub-axial mush zones), and variations in mantle source compositions and extents of melting. Various petro-geochemical models/programs (e.g. MELTS, Petrolog, EC-AFC, INVMEL) have been developed that allow us to model many of these processes. Radiogenic isotopic values (e.g. Sr, Nd, Hf, Pb), unaffected by magmatic processes, are also critical in «fingerprinting» different mantle sources.
Examples from the intermediate spreading rate JdFR and fast spreading EPR exemplify how these different data and models have been used to decipher mechanisms of crustal accretion. Some of the important discoveries that have been made include:
1. Although volcanism is largely focused at the Axial Summit Trough (AST) off-axis volcanism occurs up to 8 Km from axis ? consistent with U-series isotopes, off-axis hydrothermal venting, and recent seismic imaging of melt off-axis.
2. Individual eruptions are relatively homogeneous but have a variety of flow morphologies
3. Off-axis flows tend to be more evolved (lower MgO) and in some cases more «enriched » (higher K/Ti, La/Sm, more radiogenic) indicative of complex plumbing systems
4. Crustal/volatile contamination occurs off-axis in the shallow crust
5. Highly evolved magmatic systems (andesitic-dacitic) develop at ridge crest off-sets ? AFC processes and magma mixing occur in punctuated events within cooler crust
6. Magmatic segmentation occurs at small spatial scales (10's of km) defined by 4th-order discontinuities)
7. Repeat eruptions at 9°50'N on the EPR provide evidence for magma mixing/cooling on decadal time scales
8. Eruptions are associated with upper crustal seismic events and occur as pulses over months
9. Gabbroic xenoliths indicate complex crystal-melt interactions at various depths in the crust
10. Mantle source end-members (and primary magmas) are likely to be more incompatible element depleted and enriched than sampled by typical mid-ocean ridge basalts.

Large scale hydrothermal frow in a edimented spreading center in the northern Gulf of California, Mexico

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The tectonic setting prevailing in the region indicates that the Gulf of California likely includes an undetermined number of short spreading centres with hydrothermal systems in different stages of development. However, active sea floor spreading phenomena has been documented only in three of the 8 tectonically active basins located in the Gulf of California.
Heat flow measurements, seismicity data, gas composition, radon concentration, detailed bathymetry, profiler sections and organic matter maturation data provide supporting evidence to infer the occurrence of strong hydrothermal circulation at the Wagner and Consag basins in the northern Gulf of California.
Bathymetry and profiler data revealed large vertical displacements due to faulting that disrupted the sedimentary column, which is more than 7 km thick. These faults play the role of channels through which hydrothermal fluids ascend up to the seafloor. More than 300 flares were mapped. Beneath the plumes, sedimentary reflectors were enhanced and acoustic blanking indicative of subsurface gas accumulation was observed.
Heat flow measurements were collected with a 6 m long FIELAX® probe. Data were processed using our software. The high sedimentation rate (>3.3 mm/yr) would decrease the measured heat flow values; as the data were not corrected for sedimentation, presented heat flow figures should be taken as minimum since the actual values would be higher. Seasonal changes in bottom temperature are not significant because of strong mixing phenomena. The sea water samples for 222Rn measurements were immediately analyzed after recovery by a «RAD 7» coupled with an additional RAD-H2O accessory.
The gas sample obtained in one of the flares was analyzed aboard using a gas chromatograph and the results indicate a relation CO2/CH4 = 5.75, which is the expected ratio for an equilibrium temperature of approximately 200°C. Chemical studies of the sediments from the Wagner Basin show that they have been subject to alteration of the sediment organic matter due to hydrothermal activity, similarly to what has been reported in the Central Gulf of California (Guaymas Basin), where high heat flow has been related to hydrocarbon generation and thermogenic methane abundance.
Thermal gradient varies from 0.01 to more than 12 °C/m and thermal conductivity has an average value of 1.2 W/m°C, which results in calculated heat flow values that vary from 15 to more than 10 Wm-2. Only three stations presented heat flow values below or equal to the Earth's mean value (41 mWm-2) and the rest of the measurements is well above this value. The average value of 1875 mWm-2 indicates a heat output >2000 MWth assuming for the calculation only the area where hydrothermal manifestations have been observed. 222Rn anomalies and main fault traces coincide with positive heat flow anomalies and define deep convection cells that confirm that heat-mass transport phenomena take place in the basins where intense faulting increases permeability of the sedimentary layers.

Déchirures: Break-up and Tear-off

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Birth of oceans starts with break up of continents followed by spreading and sometimes long drifts of detached continental fragments travelling across the globe.

My marine career started in the late seventies with Jean Francheteau, studying the northern termination of the EPR (RITA and RISE projects) at the entrance of the Gulf of California, recently splitting Baja California from NW Mexico. This unforgettable scientific experience, coupled with a personal complicity, traced for all my life my independent scientific approach of continental break-ups in Southeast Asia (South China, Sulu, Celebes, Andaman seas).

Working with Jean provided me, at that time, as a young land geologist working in the Sonora desert and Baja California, with an inestimable experience to later combine onshore and offshore observations in similar key tectonic settings around the globe where continents are rapidly breaking up or tearing off.

In this short presentation, I will illustrate the birth of a young ocean within a complex tectonic setting and selected case study, the Andaman Sea.

This "déchirure" or tear-off, is not only geologic, but obviously personal. Have a nice drift Jean.

Tectonic initiation of serpentinization: mesh-texture development in exhumed peridotites, at slow and ultraslow-spreading ridges

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Tectonic exhumation at slow- and ultra-slow spreading ridges leads to wide exposures of mantle-derived material on the seafloor. The contact between seawater and peridotites produces a widespread serpentinization of those ultramafics. As some authors have shown, the oceanic lithosphere can be altered down to 3 to 4km deep. It is commonly inferred that fractures allow penetration of seawater at depth. However debate is still active on the origin of the fracturing. Several hypotheses have been developed in the literature: thermal cracking due to rock cooling, tectonic fracturing caused by spreading movements and footwall flexure, or hierarchical fracturing related to the volume increase associated with serpentinization.
At microscopic scale, olivine replacement by serpentine progresses from the fractures network toward the centres of olivine relics. The alteration texture is called mesh-texture and has been widely described in the literature. Here, we propose a model for mesh-texture development, from the initiation of serpentinization to the fully serpentinized state.
We base this model on a microstructural and petrographic study of peridotites drilled and dredged along the Mid-Atlantic Ridge during the ODP-Leg 153 cruise (RV JOIDES Resolution) and the Serpentine cruise (RV Pourquoi Pas ?), and on peridotites dredged along the Southwest Indian Ridge during the Smoothseafloor cruise (RV Marion Dufresne).
Large fractures are observed at macroscopic scales. In thin sections, up to two sets of conjugate fractures control the meshwork. Pseudo-columnar lizardite grows from these fractures into the olivine relicts. Thin, continuous, en-echelon fractures are interpreted as tectonic. Orthogonal and shorter fractures are interpreted as hierarchical and due to volume increase. The domains of pseudo-columnar lizardite that develop from these secondary fractures tend to be thicker. In the studied samples, the serpentinization degree varies from 20% to 100% and no new fracturing appears to develop in this range.
We conclude that tectonic fracturing associated with exhumation initiates the serpentinization. Seawater progresses at depth through these fractures and hydrates the peridotites. The volume increase in the early stages of the reaction produces hierarchical fracturing in olivine relics; these secondary fractures generally accommodate the major part of the serpentinization.

Crustal accretion and hydrothermal convection patterns at fast-spreading ridges

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2 : Oslo University
3 : Cornell University

New oceanic crust is continuously created along the mid-ocean ridge systems that encircle the globe. At intermediate to fast spreading ridges, crustal accretion occurs by the crystallization of mantle melts accumulating in at least one shallow on-axis melt lens. Seismic reflection data shows that its depth is inversely correlated to spreading rate. A tomographic study of the East Pacific Rise imaged the temperature structure of the lower crust showing a narrow region of high temperatures throughout the crust that widens at moho depths (Dunn et al., 2000). Further off-axis, nearly horizontal isotherms that steepen towards the ridge axis are described. The restricted width of the region with anomalously high temperatures suggests that hydrothermal convection extend well into the lower crust and potentially to moho level.
This imaged thermal structure could be used as a proxy for the likely hydrothermal convection patterns if numerical models were able to resolve both the crustal accretion process and hydrothermal cooling. Due to the different time scales of hydrothermalism and crustal accretion, numerical models have so far focused on only one of the two processes. Here we present the results of newly developed model that resolves simultaneously crustal and mantle as well as hydrothermal flow within one finite-element model (Theissen-Krah et al., 2011). The formation of new oceanic crust is approximated as a gabbro glacier, in which the entire lower crust crystallizes in one shallow melt lens. The solid velocities are described by Stokes flow for incompressible viscous fluids. Magma injection in the diking region and the melt lens, where crystallization of the upper and lower crust takes place, are implemented via a dilation term. Hydrothermal cooling is resolved by solving for Darcy fluid flow for pure water.
In a first application of this model, we have revisited the well-known observation that the depth of the melt lens correlated inversely with spreading rate (e.g. (Morgan and Chen, 1993)). Our modeling results show that only a narrow range of crustal permeabilities are consistent with observed melt lens depths, which are primarily controlled by the on-axis permeability. The off-axis permeability determines the width of hot lower crust. These findings have motivated a second set of numerical experiments, in which we also the fitted the off-axis temperature structure. For this it was necessary to allow for hydrothermal cooling at depth and include a high near-axis permeability region possibly created by thermal cracking as previously proposed for the Oman ophiolite (Nicolas et al., 2003). Furthermore, permeabilities must decrease as the crust ages and moves away from the ridge. Our results further suggest that two hydrothermal convection systems develop: one shallow on-axis system and a second deep reaching near-axis (and across axis oriented) system. Both systems together are responsible for the thermal structure observed at fast spreading ridges

Building of the deepest gabbroic crust at a fossil slow spreading centre (Pineto gabbroic sequence, Alpine Jurassic ophiolites)

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The Pineto gabbroic sequence (Corsica, France) is a poorly known lower crustal section from Alpine Jurassic ophiolites. The sequence is mainly constituted by gabbroic rocks whose rock compositions indicate crystallization from MORB-type melts, locally crosscut by N-MORB basalt dykes [1]. In particular, the Pineto gabbroic sequence is estimated to be ~1.5 km thick and mainly consists of clinopyroxene-rich gabbros to gabbronorites near its stratigraphic top and of troctolites and minor olivine gabbros in its deeper sector. The sequence also includes olivine-rich troctolite and mantle peridotite bodies at different stratigraphic heights. The composition and the lithological variability of the Pineto gabbroic sequence recall those of the lower crustal sections at slow and ultra-slow spreading ridges [2; 3], although the studied sequence is distinct in the high proportion of troctolites and olivine gabbros, which approximately constitute 2/3 of the section. In particular, the olivines and the clinopyroxenes from the troctolite-olivine gabbro association have high Mg# (89-82 and 90-86, respectively) indicating that the deepest portion of the fossil lower oceanic crust was chemically primitive, and of cumulus origin. The mineral chemical variations document that the origin and the evolution of the Pineto gabbroic rocks were mostly constrained by a process of fractional crystallisation. However, the clinopyroxenes from the olivine gabbros and the olivine-rich troctolites record the infiltration of olivine-dissolving, Cr2O3-rich melts. These melts likely formed by incongruent dissolution of pyroxenes from harzburgites/lherzolites at the top of mantle dunitic conduits or at the crust-mantle transition. Cooling rates of the troctolites and the olivine gabbros were evaluated using the Ca in olivine geospeedometer [4]. We obtained high and nearly constant values of -2.2 to -1.7 °C/yr log units, which were correlated with the building of the Pineto gabbroic sequence through different, small scale gabbroic bodies intruded into a cold lithospheric mantle. A similar process of growth also matches the architecture of the Pineto gabbroic sequence.

Rererences cited:[1] Beccaluva, et al. 1977, Contributions to Mineralogy and Petrology, 64, 11-31. [2] Blackman, et al., 2006, Proceedings of the Integrated Ocean Drilling Program, Volume 304/305: doi: 10.2204/iodp. proc.304305.2006. [3] Dick et al., 2000, Earth and Planetary Science Letters, 179, 31?51, doi: 10.1016/S0012?821X(00)00102?3. [4] Coogan et al., 2007, J. Petrology, 48, 2211-2231.

Use of thermocouple arrays for study of microbial colonization in very young (days to weeks old) vent deposits

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Investigations of microbial colonization of very young hydrothermal deposits were carried out in 2009 at hydrothermal vents in the Lau Basin (SW Pacific), and in Guaymas Basin, Gulf of California. Active chimneys were razed, and then arrays of temperature probes (8 titanium-encased probes with their tips placed within a titanium cage) were placed over the active flow. A total of 14 array deployments were made at 9 vents in 5 different vent fields. Similar morphology beehives (with porous fine-grained interiors and steep temperature gradients across the outermost more-consolidated «wall») formed at 2 of the 3 vents in Guaymas Basin (in 2 and 5 days at one vent and 3 and 15 days at a second), and at one vent each in the Kilo Moana (in 3 days), Tahi Moana (in 2.5 days), and Tui Malila (in 3 and 8 days) vent fields in the Lau Basin. At the Mariner vent field in the Lau Basin, open conduit, thin-walled chimneys formed at 3 different vents (in 3 days at one vent, in 3 and 11 days at a second vent, and in 13 days at a third vent). A third chimney type, a lower temperature (Preliminary diversity data from the 6- and 15-day Guaymas deployments show an increased diversity of bacteria with time. Initial colonizers are primarily sulfur-oxidizing Epsilonproteobacteria, with members of the Aquificales and Deltaproteobacteria appearing in the 15-day deposit. In contrast, the Archaea showed very little change in diversity over time, with members of the genera Thermococcus and Methanocaldococcus present in all samples analyzed, irrespective of location and timing of sampling. These results from the Guaymas diffuser deployments differ significantly from a 72-hour test array deployment done in 2008 at Rainbow vent field on the Mid-Atlantic Ridge. At the Rainbow vent, deposited amorphous soft material was colonized only by the sulfate-reducing archaeum, Archaeoglobus. Diversity data from the other array samples of known age and thermal history, combined with fluid chemistry data (fluid samples were collected from 7 of the 10 vents), will allow comparisons to data from 2003 (Page et al., 2008, Env. Micr.) and study of the potential impact of fluid chemistry, mineralogy/texture, and time on microbial colonization and succession.

Jean FRANCHETEAU
1943 - 2010
Massive deep-sea sulphide ore deposits discovered on the East Pacific Rise
REVUE DU PALAIS DE LA
découverte
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Naissance des océans
LES HOMMES ET LEUR TEMPS
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The East Pacific Rise near 21°N, 13°N and 20°S: inferences for along-strike variability of axial processes of the Mid-Ocean Ridge
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The New York Times
ved Near Floor of Mid-Atlantic Rift
Molten Lava Believed Near the Floor of Mid-Atlantic Rift Valley
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