Report on the ECORD MagellanPlus workshop:

"Mantle, water and life: the ultramafic-hosted Rainbow hydrothermal field"

10-12th June 2015, Lyon, France

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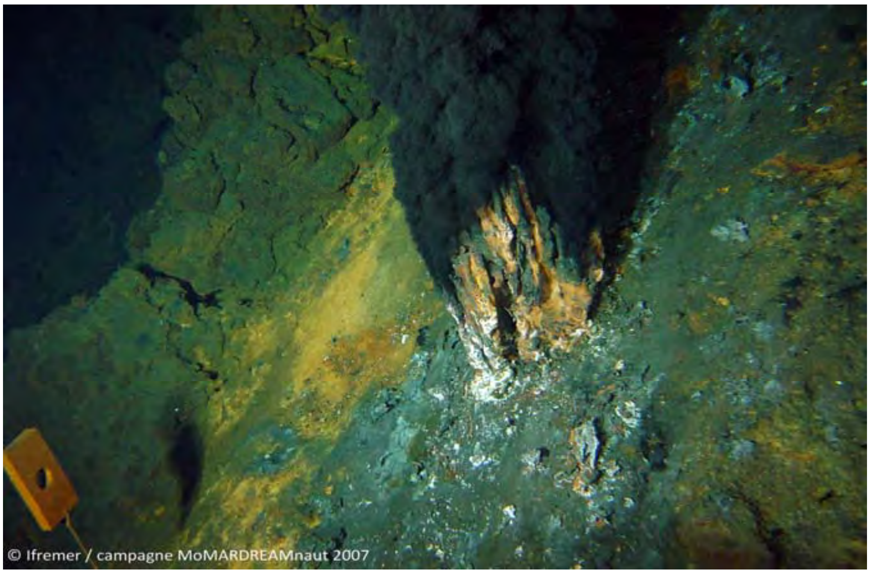

Report content:

1) **Short summary**
2) **Objectives**
3) **Program**
4) **Participants**
5) **Main outcomes and future plans**
6) **Budget**

1) Short summary

Understanding interactions between the mantle, fluids and subsurface microbial ecosystems is one of the main decadal goals of the new IODP science plan, and is a major research theme of the Deep Carbon Observatory (DCO) community. The Rainbow massif, located at 36°14'N along the mid-Atlantic ridge (MAR), is one of the most spectacular expressions of the interplay between magmatic, tectonic, hydrothermal, and biological processes at slow-spreading ridges. It thus provides the opportunity to address these first order questions at a single location, through integrated studies. This massif hosts the Rainbow hydrothermal field, which is rooted in deep-seated rocks (gabbroic and mantle-derived rocks) most probably exhumed along a detachment fault now thought to be inactive. As opposed to the Atlantis Massif (30°N; MAR), that hosts the off-axis, alkaline, low-temperature Lost City field that has been investigated during three IODP expeditions (304 and 305 in 2006 and 357 in 2015), the Rainbow massif hosts a near-axis, acidic, high-temperature hydrothermal site, venting fluids at 350-365°C and exhibiting the highest and most exceptional iron concentration of other known hydrothermal vent fields. In addition it is associated with Cu-Zn-(Co) massive sulfide mineralizations. Hence, the Rainbow massif represents a pertinent complementary target for improving our understanding of interactions between seawater-derived fluids, mantle and the heterogeneous crust generated at slow-spreading ridges, and the tectonic processes associated with deep rock emplacement. Addressing the functioning of such systems requires direct observation and sampling of the subsurface, with an access to the third (vertical) dimension that can only be achieved by drilling.

To promote and develop a drilling proposal on the Rainbow massif, we organized a 3-days MagellanPlus workshop in Lyon, France, June 10^{th}-12^{nd} 2015, co-funded by ECORD and the Deep Carbon Observatory. The 26 participants from 7 different countries (Italy, France, Germany, Norway, Switzerland, UK, and USA) brought their complementary expertise in geophysics, geology, geochemistry and biology to establish an up-to-date synthesis of our knowledge on the Rainbow massif and more generally on ultramafic-hosted hydrothermal sites. Discussions identified the key questions that remain to be addressed to fully understand the drivers and geometry, as well as the geochemical and biological consequences of these hydrothermal systems. The Rainbow Massif was recognized as an optimal target, given the extensive knowledge we now have about Rainbow in all fields and the large amount of work conducted in this area in recent years that reflects the strong scientific interest of the community. It was recognized that drilling is now a necessary step to move forward. Contributions from experienced scientists and specialists in drilling technologies allowed efficient discussions on possible drilling strategies that were presented in a drilling pre-proposal in April 2016.

2) Objectives

The 3-day MagellanPlus workshop on Rainbow was planned with the following goals:
(1) to synthesize existing data and our knowledge of processes occurring at Rainbow and other high-T and low-T peridotite-hosted sites, such as Logachev, Ashadze, Semenov, or Lost City.
(2) to identify remaining scientific questions regarding the functioning of these systems, i.e. nature of the heat source, composition of the lithosphere involved in fluid-rock reactions, controls on fluid composition and fluid paths, nature and origin of organic compounds, extent of the deep biosphere.
(3) to plan a coordinated research effort in the coming years, that integrates the role of ocean drilling in advancing our understanding of the Rainbow hydrothermal system, that could become the high-T reference site for ultramafic-dominated settings.
(4) to discuss a drilling strategy (e.g. location of target sites, multiple shallow holes versus a deep hole, seabed rock drill, CORK and instrumented holes …) and the relevance of a long term monitoring of boreholes with a particular attention to the environmental impact issues for the ecosystem.

3) Program

Tuesday June 9th:
17:00 – 20:00 Registration at the Villemanzy residence
19:00 – 20:00 Welcome to participants: dining cocktail at the Villemanzy residence

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* *keynote talks*

Wednesday June 10th:
9:30 – 9:45 Introduction by the steering committee: Objectives of the workshop

9:45-12:25 Existing dataset/knowledge on the Rainbow massif and hydrothermal field

- 9:45-10:15 : Geology and hydrothermal signature of the massif
  M. Andreani* (U. Lyon, France)
- 10:15-10:45 : Tectonics and seismic structure of the massif
  J.P. Canales* (WHOI, USA)

Coffee break

- 11:15-11:45 : The magnetic signature of ultramafic-hosted hydrothermal systems. F. Szitkar* (Geomar, Germany)
- 11:45-12:05 : High resolution bathymetry, magnetics, and photography on the Rainbow site and vicinity : insights on ultramafic-hosted hydrothermalism, remaining questions to address by drilling. J. Dyment (IPG Paris, France)

- 12:05-12:25 : Heterogeneous and asymmetric crustal accretion: new constraints from multi-beam bathymetry and potential field data from Rainbow
  M. Paulatto (Geoazur, Nice, France)

12:30-14:30 Lunch and poster session

- 14:30-15:00: Sulfide mineralization in an ultramafic-hosted seafloor hydrothermal system. A.F. Marques* (Bergen Univ., Norway)
- 15:00-15:20: MARINER: a multi-disciplinary geophysical study of the Rainbow massif and surrounding area.
  R. Dunn (Hawaii Univ., USA)
- 15:20-15:50 : Nature of fluids venting at Rainbow active site
  C. Konn* (IFREMER, France)

Coffee break

16:20-17:30 Fluid-rock-microbe interactions in ultramafic systems:
- 16:20-16:50: Microbial ecosystems at ultramafic-hosted hydrothermal sites
  G. Erauso* (MIO, Marseille, France)
- 16:50-17:10: Energy and habitat chemical constraints potentially driving the dynamics of Rainbow chemosynthetic communities
  N. Le Bris (LECOB Univ. Paris 6, France)
- 17:10-17:30: Deciphering carbon turnover in the serpentinizing oceanic lithosphere through a multi modal approach at the microscale
  B. Ménez (IPG Paris, France)

17:30-18:00 Discussion/Concluding remarks

19:00 Dining at the Villemanzy residence

Thursday June 11th:

9:30 – 11:45 Group discussions and Plenary Session *with Coffee break***:**
- Main open scientific questions on Rainbow
- How to address these questions?

11:45-12:15 Similar systems / Analogs
- 11:45-12:15: Drilling the Atlantis Massif: similarities, differences, and complementarities with Rainbow
  G. Fruh-Green* (ETH, Switzerland)

12:30-14:00 Lunch and poster session

14:00-15:30 Similar systems / Analogs

- 14:00-14:20: 13°N MAR: tectonics and hydrothermalism on oceanic detachment faults. J. Escartin (IPG Paris, France)
- 14:20-14:40: The Easternmost southwest Indian Ridge: a melt-poor natural laboratory for the study of ridge processes. M. Cannat (IPG Paris, France)
- 14:40-15:00: Serpentinization and fluid pathway in tectonically exhumed peridotites from the Southwest Indian Ridge (62°-65°E).
  S. Roumejon (Univ. Bergen, Norway)
- 15:00-15:20 : Formation of heterogeneous slow-spread oceanic lithosphere
  M. Godard (Geosciences Montpellier, France)

Coffee break

15:50-17:30 ***Group discussions and Plenary Session***

- Main open scientific questions on ultramafic-hosted systems
- How drilling/monitoring Rainbow can help

19:30 Dining at "l'Etage" restaurant *(http://www.letage-restaurant.com/)*

Friday 12th:

Drilling technologies/long term monitoring in serpentinites/hot rocks

- 9:30-10:00: Existing Drilling / Coring technologies used by the Ocean Drilling Program: S. Migdley* (TAMU, USA)
- 10:00-10:20: ODP and IODP scientific drilling at Oceanic Core Complex.
  B. Ildefonse (Geosciences Montpellier, France)

10:20-12h25 Group discussions and Plenary Session *with Coffee break*:

- Drilling at Rainbow: why, where and how?
- Wrap up on designing a drilling experiment at Rainbow

12h30 Lunch

13:30 Synthesis and outline for a drilling proposal *(for interested co-proponents)*

Posters

- Boschi C. (Italy) : Ultramafic-hosted copper deposits from Liguride Ophiolites in Southern Tuscany
- Delacour A. (Univ. St Etienne, France) : Serpentinization and element mass transfers at mid-ocean ridges

- Lacinska A. (BGS, UK): The importance of the structure and chemistry of serpentine minerals for CO_2 sequestration through mineral carbonation
- Toffolo L. / Martin S. (Italy): The Cogne magnetite deposit (NW Italian Alps): is it an ophiolitic analogue of Rainbow ?
- Roussel E. (Ifremer, France): Microbial ecology -Fluid-Rock-microbe interactions

4) Participants

The Rainbow workshop was attended by 26 participants from 7 different countries (Italy, France, Germany, Norway, Switzerland, UK, and USA), including 4 young scientists. 13 scientists, who were not available to come to the workshop, also expressed their interest to the outcomes and to a possible drilling proposal. The list of participant is provided below, as well as a group picture.

List of participants to the workshop

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Invited speakers			
* Young scientists			

People who expressed their interest in the subject and to the workshop outcomes

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Invited speakers			
* Young scientists			

Group picture at the Villemanzy Residence, Lyon, France.

5) Main outcomes and future plans

Oral presentations, posters and group discussions during this workshop allowed to fulfil the objectives. Discussions identified open questions that could be addressed at the Rainbow Massif, notably by drilling. Notably, this workshop lead to of a drilling pre-proposal that was submitted to IODP in April 2016.
A summary of present-day knowledge and future plans are reported below, as well as the proposed drilling objectives and strategy.

Main characteristics of the Rainbow massif and its hydrothermal activity

The Rainbow massif, located 36°14'N on a non-transform offset of the Mid-Atlantic Ridge (MAR), hosts the active Rainbow hydrothermal field (RHF), and is one of the most spectacular expressions of high-temperature (high-T) hydrothermalism hosted in an ultramafic substrate. It shares the main characteristics of other ultramafic fields that vent fluids at T>300°C and give rise to the development of Cu-Zn-(Co-Au) massive sulfide mineralizations with characteristics comparable to those of mafic VMS (Volcanogenic Massive Sulfides ore deposit) (*Marques et al.,* 2007). The modified term "mafic-ultramafic" VMS was recently introduced within the USGS VMS model to acknowledge the discovery of such mineralization on a mid-ocean ridge environment with serpentinites on the footwall (*Shanks and Koski*, 2012). Of these sites, the geological context, structure, and hydrothermal activity are best studied at Rainbow after >20 years of research since its discovery.

The most recent studies revealed two additional fossil fields (Clamstone and Ghost City) associated with alkaline low-temperature (low-T) hydrothermal discharge, similar to the Lost City hydrothermal field (Atlantis Massif, MAR) (*Lartaud et al.*, 2010, 2011). This ephemeral hydrothermal activity likely overlapped with that of the RHF, without any apparent spatial-temporal progression (Figure 1).

Surficial rock sampling allowed sketching a geological and hydrothermal "map" of the massif (*Andreani et al.,* 2014). Markers of high-T hydrothermal activity (~350°C) are restricted to some samples from the RHF with Cu-Zn-(Co-Au)-bearing sulfide mineralizations and enrichments *(Fouquet et al.,* 2010; *Marques et al.*, 2006; *Shanks and Koski*, 2010). The mineralized area correlates with a strong positive magnetic anomaly (Figure 3) attributed to a second generation of magnetite accompanying sulfides in the stockwork (*Marques et al.,* 2006; *Szitkar et al.,* 2015). This high-T stage overprints pervasive basement alteration due to peridotite serpentinization at ~160-260°C, and a more diffuse, lower-T hydrothermal activity (<220°C), indicated by anomalously high As, Sb and Pb contents, is also inferred at various locations including the fossil sites (*Andreani et al.* 2014).

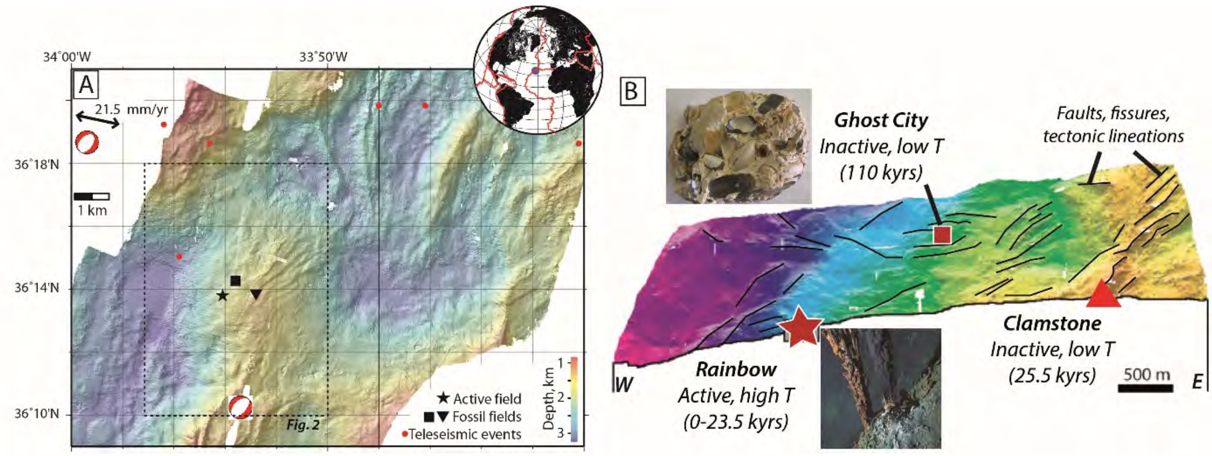

Figure 1 A) Location of the dome-shaped Rainbow massif at the center of a right-stepping non-transform offset (NTO) separating the AMAR and South AMAR ridge segments of the Northern MAR (*Gracia et al.*, 2000), that spread at ~ 21.5 mm/yr (*Le Douaran et al.*, 1982). Similar massifs are found both along-axis (*Gracia et al.*, 2000), and off-axis in this area where a series of similar massifs succeeded to each other during the last 3.5 Myr (*Paulatto et al.*, 2015). **B) Location of the active Rainbow field and of the fossil Clamstone and Ghost City fields** on the Rainbow massif with their estimated ages (*Lartaud et al.*, 2010, 2011). Modified from *(Andreani et al., 2014).*

A recent seismic survey of the Rainbow massif and adjacent spreading segments imaged the potential heat source of the RHF, in addition to determining the internal structure of the massif (*Dunn et al.*, 2013; *Canales et al.* 2013, 2015; *Paulatto et al.*, 2015). Seismic reflection images show the presence of partially molten sills at depth directly beneath RHF (Figure 4A) (*Canales et al.*, 2015). This underlying heat source is consistent with present-day fluid and mineralization analyses (*Douville et al.*, 2002; *Marques et al.*, 2007; *German et al.*, 1996, 2010). The seismic data also suggest that the underlying seismic structure represents variable extents of alteration, which may be directly link to the different types of hydrothermal activity (*Dunn et al.*, 2013; *Canales et al.* 2013). They reveal a complex three-dimensional structure, with a high-velocity, cone-shaped lithospheric volume at the core of the Massif that shoals near the seafloor in the vicinity of the active and fossil sites. This high-velocity core is capped by a lower-velocity layer dipping and thickening away from the hydrothermal area.

Decadal time series study of the geochemistry of hydrothermal fluids show that the system is stable over time and that the activity is sustainable. One of the most striking facts about the Rainbow fluids is their extremely high concentration in Iron which remains a question to be addressed. In addition, both the high-T and newly discovered low-T sites of the RHF are favorable environments for abiogenic synthesis. Note that the presence of both type of venting in the same field constitutes a dreamed study site for organic geochemistry. Numerous organic compounds are present in the RHF fluids but their origin (biogenic vs abiogenic) is still unknow (*Konn et al.*, 2009). To that respect, by drilling we would gain access to deeper material and possibly answer that question. The concentration and role of organic compounds are not well constrained either although their ligand capacity certainly affect metal transportation and bioavailability. They therefore very likely impact biological communities and biogeochemical cycles.

Mixing the RHF fluids and seawater sustain some of the highest catabolic energy yields of numerous hydrothermal fields modelled (*Amend, et al*., 2011) while primary producers are less extensive compared to other MAR fields (*N. LeBris*, workshop presentation). The different types of hydrothermal activity hosted by Rainbow massif result in distinct geochemical environments, providing a high diversity of chemosynthetic habitat for the micro and macro biota. Volatile and energy-rich fluids with potential for abiogenic organosynthesis superimposed upon high T, acidic environments more typical of ridge-axis habitats also offer potential for novel microbial biodiversity, unique from either the typical high temperature or the low-T ultramafic-hosted systems. Hence, Rainbow holds the main clues for understanding the vent ecosystems diversity and functions over space and time. More generally, characterization and quantification of rock-hosted subsurface biosphere, notably in ultramafic environments, is nascent and requires integration into compilations of global microbial abundances and to biogeochemical cycles.

Future plans

Rainbow Massif features a variety of vents in a well-established geological context, which provides a unique opportunity for studying and comparing reactions between fluids, mantle rocks and ecosystems in the hydrothermal upflow zones of both an active, high-T and a fossil lower-T vent system. We propose sampling the sub-surface to a few hundreds of meters drilling both types of hydrothermal systems, as well as the variably altered host rock. This will provide new insights into how these processes dynamically interplay in MOR environments. National oceanographic cruises, with wide AUV surveys, would also be valuable before drilling to complete the available microbathymetric data and map in details wider areas in the vicinity of the potential drilling sites, notably to identify landslides.
Programming national oceanographic cruises before and after drilling would allow to equip the site with fluid sensors (T, pH) and sample ecosystems for monitoring environmental changes (both chemical and biological) due to the exploitation and their consequences.

Scientific Objectives and drilling strategy

We propose drilling three sites to 200-500 m below seafloor (mbsf) at the Rainbow massif (1) near the high-T, acidic, active Rainbow field, (2) near the low-T, alkaline, fossil Clamstone field, and (3) into a lithospheric body with high seismic velocities (less altered and fractured). Cores from these holes will sample fluid-rock-ecosystem reactions (alteration, mineralizations, biosphere, fluids) from different styles of hydrothermal activity within a variably altered lithospheric mantle. Geological and

petrophysical core data and logging results will constrain links and feedbacks between deep structure, fluid circulation, hydrothermal styles, and vent locations.
Main questions are: 1) Are hydrothermal fluid pathways controlled by the heterogeneous underlying structure? Or is the structure a result from fluid circulation patterns controlled by late-stage tectonics? 2) Are the different hydrothermal sites linked to each other or are they independent systems with distinct histories of fluid-rock-microbe interactions?
The scientific objectives that will allow us addressing those questions are:

1) Compare the nature/conditions of fluid-rock reactions and associated bio-geochemical processes at end-member ultramafic-hosted hydrothermal sites, and explore their evolution with depth.
2) Establish the nature of the seismically distinct basement units and their relation to magmatism, alteration, deformation, and fluid flow.
3) Study the temporal evolution of hydrothermal activity from rocks sampling and measurement of associated biodiversity.
4) Constrain the present-day fluids and deep biosphere by characterizing active processes with in-situ sensors, notably measuring and monitoring dissolved H_2 and pH.

Relevance to IODP new science plan

Fluid-rock interactions associated with hydrothermal circulation in young oceanic lithosphere impact ocean chemistry, the subseafloor biosphere and the seawater communities. When mantle rocks are involved, the consequences include lithospheric weakening due to serpentinization and production of H_2 and possibly abiogenic organic compounds that can promote the development of a deep biosphere and sustain seafloor communities. These processes play a vital role in the redox cycling of carbon and other elements as well as the storage and stability of CO_2 in the seabed. Ultramafic-hosted hydrothermal systems are thus key to understand the *interactions between mantle, fluids and (sub)surface microbial ecosystems*, one of the main decadal goals of the new IODP science plan. In particular, this proposal directly relates to three of four major science themes of the new IODP Science Plan (NSP), i.e. "*Biosphere Frontiers*", "*Earth connections*" and "*Earth in Motion*", and encompasses *broader societal and scientific impacts*.

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6) Budget

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Inputs: 30 800 €

- DCO = 15 000 €
- ECORD = 11 000 €
- Registration fees = 4 800 €

Outputs: 30 800 €

- Travel expenses for keynote speakers = 4 000 €
- Travel/registration support for young scientist = 2 500 €
- Conference rooms = 1 600 €
- Full accommodation for all participants = 14 600 €
- Communication including website (with on-line payment) = 3 400 €
- Management = 4 700 €