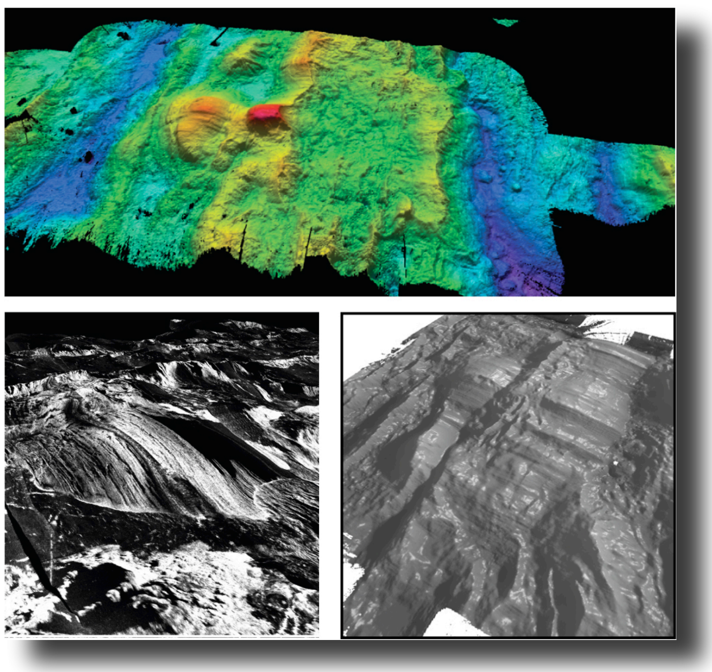
Chapman Conference

Detachments in Oceanic Lithosphere: Deformation, Magmatism, Fluid Flow and Ecosystems



Conference Report

Agros, Cyprus

8-15 May 2010

Table of Contents

Appendices

Executive Summary

Oceanic core complexes are deep sections of the oceanic lithosphere exhumed to the seafloor by long-lived detachment faults formed along the flanks of mid-ocean ridges. In order to advance understanding of the fundamental processes that control oceanic detachment faulting and OCC formation and evolution, and associated geological, chemical, and biological phenomena, we organized a **Chapman Conference on Detachments in Oceanic lithosphere: Deformation, Magmatism, Fluid Flow and Ecosystems** in Agros, Cyprus, May 8-15, 2010.

The conference was organized around 6 major science topics and consisted of 12 invited oral presentations, 78 poster presentations, 3 field trips, and discussions.

The conference delivered three specific products:

1. A community statement: *"The scientific community present at the 2010 Chapman Conference on Detachments in Oceanic Lithosphere affirmed that extension accommodated by oceanic detachment faults should be recognized as a fundamentally distinct mode of seafloor spreading that does not result in a classical Penrose model of oceanic crustal structure. This type of spreading is characterized by: formation of oceanic core complexes; tectonized and heterogeneous lithosphere; extensive exposure of gabbro and serpentinized mantle at the seafloor; some of the largest hydrogen-rich, deep-sea hydrothermal systems and mineral deposits; and large diversity in the deep-sea and subsurface biosphere. The recognition of this mode of spreading is one of the major advances in understanding plate tectonics in the last three decades."*

2. A consensus on terminology: An *oceanic detachment fault* is a large-offset normal fault formed at or in the vicinity of a mid-ocean ridge that accommodates a significant fraction of the plate separation. Offsets range from kilometers to tens of kilometers or more. Oceanic detachment faults may initiate as steep normal faults at depth, and shallow into *low angle extensional faults* through rotation of the footwall. An *oceanic core complex* results from the activity of an *oceanic detachment fault*. The *oceanic core complex* may expose the footwall of the *oceanic detachment fault*, exhuming lower crustal and mantle rocks, and be capped by a detachment fault surface that is often marked by corrugations and striations parallel to the extension direction. Alternatively, the detachment fault plane may be buried below the seafloor by rotated blocks of the hanging wall.

3. A set of recommendations to advance research in this topic and strengthen the links between the scientific community and appropriate funding agencies: (a) To establish an InterRidge Working Group on Oceanic Detachment Faults that will serve for exchange of information, resources and personnel, to coordinate efforts with other research initiatives, and to facilitate future meetings workshops to evaluate progress in the field. (b) To promote the presence of science questions related to oceanic detachment faults in the new Ocean Drilling Program, and to coordinate drilling proposals targeting oceanic detachments and core complexes. (c) To explore the possibility of creating a new program within the NSF that would support multidisciplinary research on this topic. (d) To edit a *Special Theme on Oceanic Detachments* in the journal *G-cubed* that would gather contributions from participants to this meeting and the wider community, and to publish an article to *Eos* summarizing of the results of this Conference and presenting to the broader audience the "Chapman Model" of lithospheric accretion associated with oceanic detachment faulting.

INTRODUCTION

Oceanic core complexes (OCCs) are deep sections of the oceanic lithosphere exhumed to the seafloor by long-lived detachment faults formed along the flanks of ultra-slow to intermediate-spreading mid-ocean ridges [*Cann et al.*, 1997; *Cannat et al.*, 2006; *Karson and Lawrence*, 1997; *MacLeod et al.*, 2002; *Ohara et al.*, 2001; *Okino et al.*, 2004; *Searle et al.*, 2003; *Tucholke et al.*, 2008; *Tucholke et al.*, 1998]. When active, oceanic detachment faults may constitute the sole extensional boundary between separating tectonic plates [*deMartin et al.*, 2007; *Smith et al.*, 2006; *Tucholke et al.*, 1998], and in some instances they can accommodate extension for up to 3 Myr. Exposed fault planes at the seafloor can form corrugated, dome-shaped massifs or smooth-surfaced broad hills sub-parallel to the spreading axis [*Cannat et al.*, 2006; *Tucholke et al.*, 1996; 1998].

During the last decade OCCs have increasingly attracted the interest of a diversity of bio- and geoscientists because they represent or provide access to a significant number of fundamental scientific processes that are currently being actively debated and investigated:

- Tectonic windows providing access to deep-seated rocks and processes, allowing studies of mantle flow, melt generation and migration, strain localization, and crustal accretion at mid-ocean ridges;
- A fundamental process in the generation of oceanic lithosphere that can be responsible for >50% of lithospheric accretion along slow and ultra-slow spreading centers;
- A system that provides a unique setting for sustaining both long-lived, high-temperature hydrothermal circulation as well as low-temperature, hydrogen-rich, serpentinite-related hydrothermal systems, and their associated mineral deposits and micro- and macro-biota;
- A fault zone, containing weak hydrous alteration phases, that localizes strain over extended periods of time (in some instances up to a few million years), with associated flexure and rotation of the footwall;
- A key to understand continental metamorphic core complexes formed in settings of extreme tectonic extension, as well as to detachment faults associated with extensional magma-poor continental margins.

The increased interest of the scientific community in oceanic detachment faulting and OCCs has been demonstrated during the last few years by the inclusion of special sessions in many of the most important Earth Sciences' meetings (e.g., American Geophysical Union, European Geophysical Union, Geological Society of America), featuring directly or indirectly the latest research on these processes and structures.

In order to advance understanding of the fundamental processes that control oceanic detachment faulting and OCC formation and evolution, and associated geological, chemical, and biological phenomena, we recently organized a **Chapman Conference on Detachments in Oceanic lithosphere: Deformation, Magmatism, Fluid Flow and Ecosystems**. This conference took place in Agros, Cyprus, May 8-15, 2010, and provided the ideal forum for 86 scientists from a wide range of disciplines (structural geology, tectonics, petrology, geochemistry, geophysics, geodynamic modeling, fluid chemistry, hydrothermal ecosystems, among others) to:

- Share results and synthesize our current knowledge of OCC and oceanic detachment faulting, and related processes;
- Identify the relevant scientific questions that remain unanswered, put forward new questions, and define scientific experiments and strategies to address those questions.

The conference was organized around 6 major topics:

- The Detachment Fault Zone and the Core Complex Beneath it.
- Geophysical Framework.
- Fluid Flow in Detachment Faults and Core Complexes.
- Ecology of Hydrothermal Systems Associated with Detachment Faulting.
- Implications for Continental Core Complexes and Detachment Faulting During Continental Breakup.
- New Frontiers in Oceanic Core Complex Research.

The last topic provided the community with aspects that are not directly related to oceanic detachment faulting, but may help the community to outreach other fields and expand the scope and horizons of our research.

Two full days were dedicated to 12 invited oral presentations (two per topic) to inform participants about the current state of knowledge of each topic and promising future directions of research. Contributed poster presentations (78) provided detail information on recent results and on-going investigations.

One and a half days were dedicated to discuss key relevant scientific questions related to the conference topics. These discussions, organized around 3 small breakout groups and panel summaries, served to establish the consensus among the participants on the main scientific outcome of the conference and on delineating a tentative roadmap (a) for promoting research in OCC and related themes in the near future, and (b) for strengthening the links between the scientific community present at this conference and appropriate funding agencies.

The conference also included three days of field trips:

- Introduction to the Troodos Ophiolite, visiting classic ophiolite sections including lavas, sulphide deposits, dikes, gabbros, Mt. Olympus ultramafic massif, and the Kakopetria detachment.
- Eastern Limassol Forest, where features associated with detachment faulting dominate, such as the steeply tilted Mavridhia copper deposit, or the Akapnou Forest décollement separating lavas from serpentinite.
- Western Limassol Forest, visiting, among other features, outcrops of a detachment fault separating hanging wall dikes from footwall serpentinite.

The outcome of the conference was a community statement recognizing the novelty and extraordinary importance of oceanic detachment faulting within the pate tectonics paradigm, and a consensus on the definition of oceanic detachment fault and oceanic core complex.

CONFERENCE TOPICS

Overview talks around the topics underlined the clear link that exists between oceanic detachment fault formation and accretion and composition of the oceanic lithosphere formed, and with hydrothermal and seismic activity at the ridge axis while these structures are active. Alteration and metasomatism of mafic and ultramafic rocks into alteration products (talc, chlorite, amphibolite, serpentinite) not only record these rock-fluid interactions, but also provide a mechanism for extreme fault weakening and promotion of strain localization over long periods of time. Exhumation of deep-seated rocks also promotes alteration (serpentinization), in association with serpentinization-related, H_2-rich hydrothermal circulation, which could sustain a rich and yet unknown deep biosphere. Oceanic detachment faults can also provide constraints on the stretching of the continental lithosphere along rifted margins, and on the processes of continental metamorphic core complex formation. The details of the conditions at which oceanic detachments develop (e.g., melt supply, thermal state of the lithosphere, composition and rheology), the consequences for lithospheric formation and the biosphere, and the interactions between all the active processes operating at the axis are still poorly understood, and should focus the community research in the following years.

THE DETACHMENT FAULT ZONE AND THE CORE COMPLEX BENEATH IT.

Overview talks by ***M. Cannat****, "*Oceanic Detachment Faults and the Exhumation of Gabbros and Mantle-derived Peridotites at Mid-Ocean Ridges", and ***M. Cheadle***, "Fault Rheology, Footwall Deformation and Geochronologic Constraints on the Process of Detachment Faulting at Mid-Ocean Ridges".

Exhumation of deep-seated mantle and lower crustal rocks is well documented on oceanic lithosphere accreted along slow- and intermediate spreading ridges, and can occur on ~25% of the seafloor flanking the Northern Mid-Atlantic Ridge. This observation is consistent with the presence of active detachment faulting along ~50% of the ridge length in this area. Detachment faulting thus provides a mechanism for efficient exhumation, but other uplift mechanisms, such as crosscutting faults at the axis, can also operate although they have not been documented. Furthermore, the occurrence of detachments on conjugate flanks, and displaying some overlap along the length of the axis, suggest that they can develop as conjugate faults along both flanks of the axis.

The morphology of the fault surface exposed at the seafloor shows a large variability, ranging from domed massifs with a fault plane corrugated in the direction parallel to spreading and extending ~10-20 km along-axis and ~10 km along a flow line (e.g., 13°N section of the MAR), to elongated hills sub-parallel to the ridge trend, and with a fault surface lacking striations (e.g., SWIR detachments found on 'smooth' seafloor). There is thus a wide range of morphological characteristics of the breakaway, the termination of the fault, and the overall core complex structure that is not yet understood.

The curvature, seafloor topography, and low angle of the fault at the seafloor indicate a very low effective elastic thickness (<2 km) relative to the brittle thickness at the axis (typically >5 km), leading to intense deformation in the footwall. We need to identify the mechanisms that produce this efficient weakening during detachment formation and evolution. These likely include a direct link between exhumation, deformation, hydrothermal circulation, and emplacement of magmatic bodies within the lithosphere at the core of the detachment, with the formation of weak alteration phases (talc, chlorite, serpentinite). Indicators of shear sense within the footwall are also consistent with the extreme flexure of the footwall.

Detachments also record a long history of efficient strain localization that can span several millions of years. While the deformation history may show an overall evolution from high-temperature, plastic deformation to lower-temperature, brittle deformation, there is an inherent complexity due to the lithologies of the host rock (gabbro vs. peridotite with varying degrees of alteration), the presence of water content in rocks (wet vs. dry rheologies), and the circulation of fluids. High-temperature, crystal-plastic deformation is variably sampled, and probably overimprinted by later, lower-temperature deformation along the detachment fault. The ubiquitous presence of talc-chlorite schists provides the fault weakening mechanism that allows the fault to operate at very low angles and efficiently localize strain over long periods of time.

While detachments operate, accretion is extremely asymmetric and the detachment fault takes up most of the plate separation (up to 70-80%). This asymmetric mode of accretion implies a modification of the ridge axis geometry over long periods of time, and a possible variation of the fault geometry and curvature at depth.

<u>Outstanding questions</u>:

Are the different types of detachments and their variability in characteristics an expression of the same process of deformation and exhumation? Or are do they represent fundamentally different processes or conditions of deformation?

How is deformation accommodated both along the detachment fault plane and the footwall? What are the conditions that lead to the weakening required to form long-lived oceanic detachments? How is hydrothermal activity linked to alteration of the footwall and/or circulation of fluids along the fault zone? What is the nature of the lateral transition from the detachment towards adjacent terrain?

What are the causes and consequences of asymmetric accretion as detachments take up most of the total plate separation while they operate?

What is the link between detachment formation and distribution, size, timing, and zone of emplacement of gabbroic intrusions?

GEOPHYSICAL FRAMEWORK

Overview talks by **A. Morris, "**Palaeomagnetic Insights Into Oceanic Detachment Fault Processes at Mid-Ocean Ridges", and **R. Sohn,** "Geophysical Constraints on the structure of Detachment Faults: Stone Cold Facts, Red Hot Topics, and Everything In-between".

Geophysical observations provide constraints on the geometry of the detachment fault at depth and the nature of the footwall's internal structure. However, these constraints are restricted to date to just a few examples, and whether these observations may be applied to all detachment faults requires further studies.

From a geophysical perspective, oceanic core complexes are systematically associated with 'thin' crust (i.e., rocks with either high density as constrained from gravity, or high seismic velocities consistent with lower crustal and upper mantle rocks, as constrained from seismics).

These structures may form under very specific conditions involving a complex relationship between melt supply, lithospheric thickness, and plate separation rate. Hence they may also be turned on and off by a small increase or decrease in melt supply to the axis. However, the specific set of parameters that allow their formation is not well understood, and would require a quantification of melt supply to the whole system, with constraints on the composition of the footwall and conjugate flank of the axis.

Fault geometry at depth has been inferred at the TAG detachment, where the fault is steep (~70°) below the ridge axis and shallows to ~20° at the seafloor, and requires a significant rotation of the footwall of ~50° from its root to the seafloor. This geometry is consistent with the domed shape of the fault observed at many mature oceanic core complexes.

This footwall rotation is also consistent with interpretations of paleomagnetic data from cores drilled at different oceanic core complexes, which suggest rotations ranging from 15° to >70°. These estimates are obtained by analysis of magnetic inclinations from azimuthally unoriented drill core samples, assuming that: a) remanences accurately record the geomagnetic field direction; b) changes in inclination result entirely from tectonic tilting; and c) that a simple deformation history has occurred. Such analyses result in non-unique solutions due to the scarcity of fully oriented samples from oceanic core complex footwalls. These difficulties have only recently been overcome by using borehole wall imagery to re-orient samples in order to provide robust constraints on the magnitude and axis of footwall rotation, but to date this has only been achieved at one site (Atlantis Massif, MAR, where a rotation of 50° around a ridge-parallel axis has been documented).

The magnetic remanence of young lower crustal gabbros sampled in the footwall of oceanic detachments is variable in its complexity. Some sections have been shown to carry multi-polarity magnetizations acquired during different geomagnetic polarity chrons. These sections potentially provide insights into a range of processes and their relative timing (e.g. cooling of magmatic bodies, onset of rotation, timing of serpentinization etc.).

FLUID FLOW IN DETACHMENT FAULTS AND CORE COMPLEXES

Overview talks by **A. McCaig**, **"**Hydrothermal Systems and Detachment Faulting**"** and **G. Frueh-Green**, **"**Serpentinization of the Oceanic Lithosphere: Consequences for Hydrothermal Activity and Biogeochemical Cycles**"**.

The association observed between active detachment faults and active hydrothermal fields at the seafloor is supported by the flow of high-temperature (black smoker) hydrothermal fluids through the fault zone. In addition to fault-focused flow, which may produce sites such as TAG, there is also hydrothermal flow within the footwall, to produce black smoker and low-temperature systems at core complexes (e.g., Logatchev, Lost City).

Flow is maximum within the fault zone, and seems to decrease away from it. These fluid channels may also act as thermal boundary layers, developing feedbacks between hydrothermal activity, deformation and exhumation along the detachment, and internal thermal structure, and ultimately controlling gabbro emplacement at depth. Efficient heat removal can also induce temporal variability in the geometry of the system (i.e., depth of magma chambers, detachment roots, transition between plastic and brittle deformation, etc.)

Detachment faults also exhume mantle rocks, making them accessible to fluids and promoting their alteration (e.g., serpentinization). Key aspects that affect the products of fluid-rock interaction are the depth and mechanisms of seawater penetration, the role of detachment faults, and the consequences of a heterogeneous lithosphere for alteration and mass transfer. Alteration is a complex processes with multiple phases of alteration and serpentinization and veining, and is controlled by rock composition, temperature, kinetics, local variations in activities in elements such as Si, Mg and Fe.

Early alteration phases are restricted to pyroxene hydration, while talc assemblages are related to detachment faults with focused fluid flow and high degrees of mass transfer. Late phases of fluid flow involve carbonate fill-in of veins. Pervasive serpentinization is limited to olivine breakdown at $T<425$, with maximum reaction rates at ~250°C.

Alteration results in a change of physical properties of the rock, including a reduction of density, seismic velocity, and mechanical properties (rheology). These serpentinization reactions are a sink of C, B, U and a source of Ca, Ni and Si in the hydrothermal fluids, in addition to H_2 and CH_4. These fluid compositions are critical to sustain microbial communities and possible for the viability of a deep biosphere. The production of reduced volatiles is linked to redox reactions and the partitioning of Fe, but is not limited to the classic olivine breakdown reactions to produce serpentine and magnetite. In peridotite-hosted, black smoker type systems, such as Rainbow and Logatchev, low pH, high Fe contents, and the production of H_2 and CH_4 is likely to be linked to high temperature pyroxene alteration reactions and may reflect a component of alteration of gabbroic and/or troctolitic rocks.

We still need to understand the flow pathways (discharge, recharge zones, role of fault zones) in peridotite-hosted hydrothermal systems, and obtain reliable estimates of volumes of gabbro rock/melt, as these have consequences for the quantification of mass and heat fluxes as well as the composition of fluids through this lithosphere. Low-temperature carbonate systems may have profound consequences for net fixation of CO_2 and for the microbial communities and the deep biosphere, but there are no constraints on the local or regional variability of microbial activity in these environments.

ECOLOGY OF HYDROTHERMAL SYSTEMS ASSOCIATED WITH DETACHMENT FAULTING

Overview talks by **D. Kelley**, "Linkages Among Serpentinization and Life in Ultramafic-hosted Hydrothermal Systems: The Lost City Hydrothermal Field", and **M. Perner**, "Microbial communities and metabolisms from basalt-and ultramafic-hosted vents".

Fluid composition has a profound impact on the active microbial assemblages at hydrothermal vents. Microbially mediated H_2 oxidation at moderate temperatures can significantly stimulate CO_2 fixation. However, H_2 stimulated autotrophic CO_2 fixation as well as elevated microbial H_2 consumption rates are not necessarily bound to H_2-rich environments (e.g., peridotite-hosted hydrothermal fields), but can also be associated with extremely H_2-poor vent locations (H_2 <5 nM). Even in comparatively H_2-poor vent systems, H_2 utilizing microbes can benefit from the (even very low) H_2-concentrations and can have the capacity to consume substantial amounts of H_2, with the energy gained being putatively available for driving biomass synthesis.

In contrast to the H_2 consumption and C-fixation rates, functional genes encoding key enzymes of H_2 oxidizing metabolisms (Hydrogenases) appear to be grouped according to a) H_2 concentrations, if close to the H_2 threshold values of certain electron acceptor processes, and b) the amount of admixed oxygenated seawater, which dictates the availability of (electrochemically positive) electron acceptors. This suggests that H_2 concentrations can contribute to influencing parts of the H_2-oxidizing diversity.

H_2-rich fluids (e.g., from peridotite-hosted hydrothermal fields) stimulates CO2 fixation both at H_2-poor environments, and at H_2-rich environments at moderate temperatures. 16S rNA genes do not predict metabolism associated with fluids from different types of sites as they are not limited to chemosynthetic organisms, and instead analysis of functional genes and turn over rate studies are required.

Functional genes (H_2ases) appear to be grouped according to a) H_2 concentration, if close to the H_2 threshold, and b) the amount of admixed oxygenated seawater, as it dicates the availablity of electrochemically positive electron acceptors.

Moderate to low-temperature (<150-200°C) fluid-rock reactions in the underlying ultramafic rocks result in alkaline fluids with high concentrations of abiogenically produced H_2 (up to 15 mmol/kg at Lost City), CH_4 (1-2 mmol/kg), and other low molecular weight hydrocarbons that support novel microbial communities. Lost City fluids also contain elevated acetate and formate concentrations relative to other hydrothermal fields. While formate is likely abiogenic, acetate concentration correlates with H_2 and is of likely microbial origin. There is also possible evidence for a hot sub-seafloor biosphere, as indicated by the presence of species affiliated with black smokers elsewhere (e.g., *Thermococcus)*.

Considering the global distribution of ultramafic environments and the potential importance of these systems to the origin of life and to models of Earths' earliest microbial ecosystems, study of Lost City has the potential to yield new discoveries with implications for understanding the linkages between abiotic water-rock reactions and microbial evolution.

IMPLICATIONS FOR CONTINENTAL CORE COMPLEXES AND DETACHMENT FAULTING DURING CONTINENTAL BREAKUP

Overview talks by **B. John**, "Oceanic and Continental Detachment Fault Systems: How Similar Are They?", and **G. Manatschal**, "The Role of Detachment Fault During Crustal Thinning, Mantle Exhumation and Continental Break-up at Magma-poor Rifted Margins?".

Continental core complexes share similarities with their oceanic counterparts, including a domal culmination of crust (and mantle), exposure of footwall material over large areas (100's of km^2), presence of corrugations parallel to extension, an asymmetric mode of extension, a complex fault zone with anostomosing shear zones and a down-temperature fault rock history, and extension of up to several 10's of km over time periods of up to several million years.

Continental detachment faults appear to initiate at a low angle (~20°), instead of the ~70° observed at the root of TAG OCC. The faults record deformation in the brittle domain (seismogenic), and development of weak gouges (clay primarily), leading to a fault weakening similar to that of oceanic detachment faults. Rheology in continents is controlled by the mechanical properties of quartz, which result in a much thinner lithosphere (brittle/plastic transition at <500 °C vs. 700-900°C for plagioclase/olivine in the oceanic environment).

Detachment faulting may also explain continental thinning and exhumation of the mantle along rifted margins, under conditions of reduced magma supply during extension. These outcrops record pervasive fluid reactions that alter the rocks and contribute to the reactivation of faults along the margins.

Faults display a complex structural evolution of the detachment, with ductile deformation coupled with low-temperature deformation, and an important role of serpentinization in the localization and evolution of these fault zones. Extension is also associated with serpentinization, as in the case of oceanic faults. Continental break-up is not transitional, and is related to excess magma following detachment faulting and crustal thinning.

NEW FRONTIERS IN OCEANIC DETACHMENT RESEARCH

Talks by **P. Kelemen** on "Evaluating In Situ Mineral Carbonation in near-seafloor peridotite for CO_2 Capture and Storage" and **A.-L. Reysenbach** on "The microbiology of OCC's: Implications for life in the subsurface and elsewhere in the solar system" provided a view of detachment-related research with implications beyond the direct study and comprehension of these structures.

Carbonation of olivine-rich rocks is a possible and major sink of CO_2, provided that a sufficient volume of unaltered rock is available, and a sufficiently fast reaction process is established. Major challenges include the cost and feasibility of CO_2 transport to storage sites, and the possibility of establishing a self-sustaining reaction process. This process needs to strike a balance between the reaction rate (dependent on temperature), the thermal regime at depth, and the feedback between reaction-driven precipitation/cracking and fluid circulation. Potentially, carbonation, which occurs in the oceanic environment and along oceanic detachments where mantle is exhumed, could be enhanced and activated, removing CO_2 from the water column and with no need for CO_2 transport and injection.

Oceanic detachments host long-lived, high-and low-temperature hydrothermal systems rich in hydrogen to sustain a unique and complex biosphere. New genetic techniques such as high throughput DNA sequencing are pointing to a much greater diversity and complexity of novel micro-organisms in deep-sea vents, and to a distinct identity of these populations for each vent field. Studies of these environments have implications to understand the possible conditions for subsurface biosphere elsewhere on Earth, and in other planets and moons across the Solar System.

BREAKOUT GROUPS DISCUSSIONS

One and a half days were dedicated to discuss key relevant scientific questions related to the conference topics. Each Discussion Session was organized around 3 small breakout groups formed by 18-27 participants each separated according to career stage: groups A included students and postdocs, groups B included early and mid-career scientists, and groups C formed by senior scientists. This choice promoted the participation of students in the discussions, allowing their opinions and points of view to be heard and incorporated in the final discussion.

Each breakout group included a Leader with expertise in the topics discussed, and a Scribe chosen from the postdoc and early-career pool of participants. After the 1-hour discussion all participants reconvened and the Scribes summarized the discussions of their groups.

BREAKOUT GROUPS 1A, 1B, 1C

BG 1A	Leader: R. Buck	Scribe: M. Andreani
BG 1B	Leader: J. Karson	Scribe: E. Choi
BG 1C	Leader: T. Reston	Scribe: C. Grimes

Questions:

- Can we define the following terms: Oceanic core complex, low-angle fault, detachment, large-offset normal fault, corrugations, striations, mullions, megamullions? Are these terms interchangeable, adequate, and/or Consistent with terminology used in continental metamorphic core complexes?
- How and Under Which Conditions Does Detachment-faulting Lead to the Formation and Development of OCCs?
- What are the Mechanisms and Conditions that Promote and Sustain Strain Localization Over Long Periods of Time, and the Development of an OCC?
- What are the Similarities and Differences Between Oceanic and Continental Core Complexes?
- What Can We Learn About Continental Breakup and Initiation of Seafloor Spreading From OCCs?

Terminology has been an issue of confusion that was addressed during the breakout groups. It was agreed that the terms of *oceanic detachment* or *oceanic detachment fault* and *oceanic core complex* should be retained:

Oceanic detachment faults are long-lived extensional structures efficiently accommodating a significant portion of the plate separation on-axis. *Oceanic core complex* corresponds to the footwall of the *oceanic detachment fault* that is exposed at the seafloor due to extension, and exhumes lower crustal and mantle rocks. These detachment faults may initiate as steep normal faults at depth, shallow into a *low angle normal fault* through rotation of the footwall, and in many cases they show striations and corrugations parallel to extension. The *oceanic core complex* is thus a component of an *oceanic detachment fault*.

A key aspect to understand their origin and evolution is their three-dimensional structure at depth, and the composition of the footwall so as to constrain the magmatic regime at which these structures operate, and the consequences for lithospheric composition, rheology, and physical properties.

An added complexity is that *oceanic core complexes* exhibit multiple morphological forms, which may depend on their setting, the amount of extension, and the processes behind the formation and evolution of these structures. In particular, the set of conditions that allow detachment fault formation include 1) temperature, 2) magma supply, 3) hydration, alteration and metasomatism, 4) spreading and/or deformation rates, 5) efficient and self-sustaining weakening mechanisms both along the fault itself and within the footwall. Understanding the triggering and shutting off of detachment faulting would be key to constrain the relative importance and interdependence of these processes.

Important gaps in our knowledge include the nature of the crust at the time of initiation of a detachment, and structure of the breakaway, and the structure of oceanic detachment faults away from core complexes (i.e., in depth, laterally). We also lack a complete view of lithospheric accretion in the presence of detachments, as we have limited constraints on crustal structure and composition on the conjugate flank of the ridge.

BREAKOUT GROUPS 2A, 2B, 2C

<u>BG 2A</u>	<u>Leader</u>: B. Ildefonse	<u>Scribe</u>: J.-A. Olive
<u>BG 2B</u>	<u>Leader</u>: E. Hellebrand	<u>Scribe</u>: N. Jöns
<u>BG 2C</u>	<u>Leader</u>: B. Tucholke	<u>Scribe</u>: K. Achenbach

<u>Questions:</u>

- What is the Lithological Structure of OCCs and its Variability at Scales of Meters to Tens of Kilometers?
- What is the Link Between Deformation and Magmatic

It is well established that the lithosphere associated with oceanic detachment faults is heterogeneous, and involves both mantle rocks and gabbro intrusions that have been tectonically uplifted. Fault rocks also record a complex history of deformation (in the presence of fluids) and coeval magmatic activity (dike injection). Are there areas with detachment faults forming in the absence of magmatism such as the SWIR? And how does a detachment form in a heterogeneous setting with a section lacking gabbro such as along the Kane or Atlantis detachments at the MAR?

Understanding the lithological structure or detachment faults, as well as their magmatic and thermal regime, thus requires constraints on: the size and structure of gabbro bodies (10’s of m to 10’s of km?); the zone of magma emplacement and setting relative to the detachment fault (e.g., foot wall, root of fault, cut by detachment); the timing of such intrusions (relative to each other and to the detachment fault). This heterogeneity is also key to understanding the composition of fluids circulating through the lithosphere, and the nature of alteration/metasomatism reactions that are responsible for weakening (fault, footwall).

Detachment formation could be primarily controlled by bottom up processes (e.g., mantle composition, melt supply) or bottom down processes (hydrothermal circulation, deformation of the brittle lithosphere), although feedbacks among all these processes are likely to operate.

Future studies need to both gather more information of the different types of detachments identified, and to focus on a few of these to have a comprehensive understanding of individual structures. At the present time there are too many open questions and unknowns so as to justify the choice of one or a reduced number of specific sites for integrated studies.

BREAKOUT GROUPS 3A, 3B, 3C

BG 3A	Leader: A.-L. Reysenbach	Scribe: A. Delacour
BG 3B	Leader: G. Baines	Scribe: M. Perner
BG 3C	Leader: M. Lilley	Scribe: F. Fontaine

Questions:

- What Drives Hydrothermal Circulation in OCCs and Detachment Faults?
- What are the Feedbacks Between Fluid Circulation, Deformation, and Magmatic Processes?
- What are the Biodiversity and Characteristics of Ecosystems Associated with OCCs, and How are They Related to the Style of Hydrothermal Circulation within OCCs and Along Detachment Faults?

Hydrothermal activity is hosted both along the active detachment fault (e.g., TAG), and within the footwall of the detachment at oceanic core complexes (e.g., Logatchev, Ashadze, Rainbow, Lost City). To date we have no constrain on the nature and position of the heat sources animating these systems, nor on the geometry and properties of the plumbing system. These systems also record complex interactions with a heterogeneous lithosphere (see above), and therefore their characteristics are intimately related to magmatic accretion and exhumation along the detachment fault.

Along the fault zone, seismicity provides a mechanism to generate porosity, facilitate fluid flow, and thus promote fluid-rock reactions that can produce weak mineral assemblages and further facilitate strain localization (talc, chlorite, etc.). So far, observations on microseismicity are restricted to a single site, TAG, and cannot be confidently generalized due to the large variability in types of sites observed.

Pervasive hydrothermal circulation, and association with ultramafic rocks (serpentinization) provides an ideal environment to identify and investigate aspects of deep-earth biosphere. Potentially, if this biosphere is significant, fluid compositions may provide records of biological activity. Furthermore, the stability of detachment faults (i.e., over 1 Myr) can result in stable hydrothermal sites over long periods of time. This may have consequences for the maturity of ecosystems associated with these vents, for the role of vents in the transfer of life along mid-ocean ridges, and for the occurrence of active sites away from the ridge axis possibly associated with serpentinization (e.g., Lost City).

We lack an understanding of the fluid and volatile fluxes (hydrogen, methane), and the volume of rock involved in fluid-rock reactions or its degree of alteration. These relationships may vary from site to site, and be modified by deformation and magmatism.

Open questions: Are there detachments with no hydrothermal activity associated? If so, is the deformation and thermal regime comparable to hydrothermally active sites?

FIELD TRIPS

The field trip were organized and led by J. Cann, C. MacLeod, and A. McCaig, with assistance in the field from experts from the Cyprus Geological Survey (E. Morisseau, S. Nicolaides).

TROODOS OPHIOLITE

On Monday, May 10th participants were divided in two groups. Both groups visited the same sites but in opposite order. The trip was an introduction to the Troodos ophiolite, aming:

(a) To introduce the field relations within the ophiolite north of the Arakapas transform fault, demonstrating the overall layer-cake structure of lavas over dykes over gabbro over mantle, and the processes that shaped it (e.g., Photos 1 and 2).

(b) To show that the ophiolite has been very little deformed or heated since it was formed on the ocean floor, 91 million years ago.

(c) To investigate the area of the Solea Graben where there is good evidence for very early major rotation of sheeted dykes on low angle faults during crustal construction, and where there is a possible extinct spreading axis (e.g., Photo 3).

(d) To see one of the calcium-rich, alkaline (Lost City/Blue Pool type) springs indicative of active serpentinization

Photo 1. *Outcrop of the Amiandos Fault on the Troodos-Kakopetria road. Serpentinized ultramafics (left) are yuxtaposed against gabbros (right). This fault has been recently interpreted as a detachment fault associated with an oceanic core complex [Nuriel et al., 2009].*

Photo 2. *View of the Kakopetria detachment separating highly rotated, sub-horizontal dikes (top) from sheared gabbros (bottom) [Varga, 1991].*

Photo 3. *View of the Solea graben from the Flasiana viewpoint. In the background is the Skouriotissa opencast copper mine, a massive sulfide deposit of size and chemical composition similar to those of the active TAG hydrothermal sulfide deposit at the MAR [Humphris and Cann, 2000], located on the hanging wall of an oceanic detachment fault [Tivey et al., 2003].*

EASTERN LIMASSOL FOREST

For logistical reasons the participants were divided in two groups. One group visited these sites on Wednesday, May 12th, and the other group on Thursday, May 13th. The trip visited the Eastern part of the Limassol Forest south of the Arakapas transform fault. Here the lithological units are the same as in the Troodos Massif, but without the simple layered stratigraphy seen there; instead, the units are juxtaposed in a complex way, with very significant levels of brittle faulting. The aims were:

(a) To gain an understanding of the overall structure of the eastern Limassol Forest area, in which the effects of detachment faulting predominate.

(b) To demonstrate steeply dipping lavas and interpillow sediments in the hanging wall of a detachment.

(c) To examine outcrops of two low-angle faults, one a 'bookshelf' fault that separates tilted fault blocks above the main detachment, and the other of the main detachment itself, the Akapnou Forest Décollement, separating lavas from serpentinite.

(d) To investigate the open cast pit of the Mavridhia copper deposit, itself also tilted steeply (e.g., Photo 4).

Photo 4. *Mavridhia opencast mine. The sulfide deposit (light yellow and orange colors) is sandwiched between unaltered (top) and hydrothermally altered (brown color, bottom half) lavas.*

WESTERN LIMASSOL FOREST

For logistical reasons the participants were divided in two groups. One group visited these sites on Wednesday, May 12th, and the other group on Thursday, May 13th. The trip visited the Western part of the Limassol Forest south of the Arakapas transform fault. Here serpentinized mantle rocks are exposed as E-W elongated domes, juxtaposed by extensional faults against disrupted remnants of a layered crustal sequence, including gabbros, sheeted dikes, and in places lavas. The aims of this trip were:

(a) To investigate an area of the Limassol Forest that shows a very different set of features from that seen in the eastern area.

(b) To see outcrops of a low-angle detachment fault separating hanging wall sheeted dykes from footwall serpentinite (Photo 5).

(c) To examine late igneous bodies (dykes and plutons) intruding both the footwall serpentinite and the hanging wall blocks.

(d) To investigate the evolution of the deformation of the footwall serpentinite.

(e) To see veins of calcite in serpentinite deposited from calcic spring waters.

(f) To determine an overall chronology of deformation, magmatic activity and hydrothermal alteration/metamorphism in this area.

Photo 5. *Outcrop of a detachment fault separating highly altered dikes (top) from serpentinized harzburgite (bottom).*

CONFERENCE OUTCOME

The Conference delivered three specific products that will guide research in oceanic detachment faults and core complexes in the future:

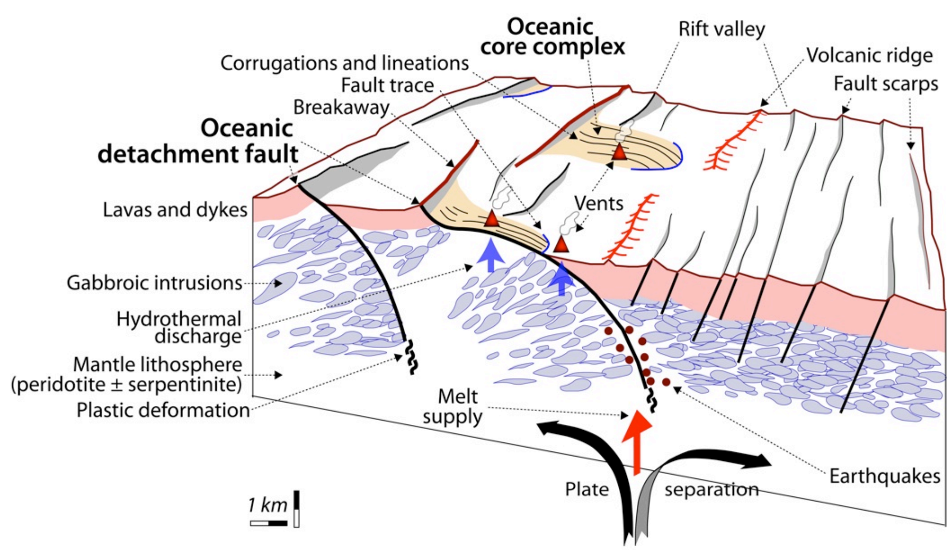
(1) A community statement emphasizing the significance of oceanic detachment faulting as a distinct mode of seafloor spreading;

(2) A consensus on the definition of oceanic detachment fault and oceanic core complex, and a cartoon showing the main features the community agrees on are known and characteristic of oceanic detachments;

(3) A set of recommendations ("the path forward") to advance research in this topic and strengthen the links between the scientific community and appropriate funding agencies.

COMMUNITY STATEMENT ON OCEANIC DETACHMENTS

"The scientific community present at the 2010 Chapman Conference on Detachments in Oceanic Lithosphere affirmed that extension accommodated by oceanic detachment faults should be recognized as a fundamentally distinct mode of seafloor spreading that does not result in a classical Penrose model of oceanic crustal structure. This type of spreading is characterized by: formation of oceanic core complexes; tectonized and heterogeneous lithosphere; extensive exposure of gabbro and serpentinized mantle at the seafloor; some of the largest hydrogen-rich, deep-sea hydrothermal systems and mineral deposits; and large diversity in the deep-sea and subsurface biosphere. The recognition of this mode of spreading is one of the major advances in understanding plate tectonics in the last three decades."



Cartoon synthesizing the 'Chapman model' of lithospheric accretion associated with oceanic detachment faulting. This model includes structural elements, architecture and composition of the lithosphere and active processes at the ridge axis. Many elements and details of the model are currently weakly constrained (e.g., size, abundance and distribution of gabbro bodies, hydrothermal flow paths, fault geometry at depth, distribution of alteration).

TERMINOLOGY

An *oceanic detachment fault* is a large-offset normal fault formed at or in the vicinity of a mid-ocean ridge that accommodates a significant fraction of the plate separation. Offsets range from kilometers to tens of kilometers or more. Oceanic detachment faults may initiate as steep normal faults at depth, and shallow into *low angle extensional faults* through rotation of the footwall.

An *oceanic core complex* results from the activity of an *oceanic detachment fault*. The *oceanic core complex* may expose the footwall of the *oceanic detachment fault*, exhuming lower crustal and mantle rocks, and be capped by a detachment fault surface that is often marked by corrugations and striations parallel to the extension direction. Alternatively, the detachment fault plane may be buried below the seafloor by rotated blocks of the hanging wall.

THE PATH FORWARD

After identifying oceanic detachment faults as a key component of oceanic crustal accretion, the community decided to capitalize on the on-going research impetus and interest.

Community coordination. The Conveners, in consultation with the Scientific Committee and the wider community, will submit in September 2010 a proposal to the InterRidge Steering Committee to establish a new Working Group on Oceanic Detachment Faults. The mandate of this WG is to be defined, but should serve for exchange of information, resources and personnel (projects, cruises, visits, etc.), to coordinate efforts with other research initiatives (e.g., IODP, Margins) to further the goals of this Conference, and to facilitate future meetings workshops to evaluate progress in the field.

Oceanic Drilling. This is seen as a key component to address the origin and structure of oceanic detachments, and the process of lithospheric accretion at the ridge axis in general. An effort should be done to coordinate the numerous proposals that target different oceanic detachments and core complexes so as to present a long-term, coherent and ambitious program for IODP.

NSF. The US community will explore the possibility of creating a new program within NSF that would support multidisciplinary research in oceanic detachments in the next years.

Dissemination of Conference results. Following the recommendation of the Community, the Conveners have received approval from the Senior Editor of the journal *Geochemistry, Geophysics, Geosystems* to open a *Special Theme on Oceanic Detachments* that would gather contributions on the topic from participants to this meeting and the wider community. More than 20 potential papers have been identified, and *G-cubed* will open the submission of manuscripts to this new there in early Summer 2010.

The results of this Conference will be reported in an article to *Eos*, which will present to the broader audience the "Chapman Model" of lithospheric accretion associated with oceanic detachment faulting.

APPENDICES

CONFERENCE SPONSORS

The conference organizers acknowledge the generous logistical and financial support of the following sponsors:

National Science Foundation

Consortium for Ocean Leadership

European Science Foundation

Cyprus Geological Survey

Deep Ocean Exploration Institute of the Woods Hole Oceanographic Institution

InterRidge

Institute de Physique du Globe de Paris

Centre National de la Recherche Scientifique

CONVENERS AND PROGRAM COMMITTEE

Conveners

Juan Pablo Canales

Woods Hole Oceanographic Institution
360 Woods Hole Rd.
Woods Hole, MA 02543, USA
jpcanales@whoi.edu

Javier Escartín

CNRS - Institute de Physique du Globe de Paris
4 Place Jussieu
75252 Paris Cedex 05, France
escartin@ipgp.jussieu.fr

Program Committee

Donna Blackman

Scripps Institution of Oceanography
La Jolla, CA 92093, USA
dblackman@ucsd.edu

Andrew McCaig

University of Leeds
Leeds, LS2 9JT, UK
a.mccaig@earth.leeds.ac.uk

Joe Cann

University of Leeds
Leeds, LS2 9JT, UK
j.cann@see.leeds.ac.uk

Eleni Morisseau

Cyprus Geological Survey Department
Lefkosia, Cyprus
director@gsd.moa.gov.cy

Mathilde Cannat

CNRS - Institute de Physique du Globe de Paris
4 Place Jussieu
75252 Paris Cedex 05, France
cannat@ipgp.jussieu.fr

Stelios Nicolaides

Cyprus Geological Survey Department
Lefkosia, Cyprus
snicolaides@gsd.moa.gov.cy

Gretchen Früh-Green

Eidgenössische Technische Hochschule (ETH)
8092 Zurich, Switzerland
frueh-green@erdw.ethz.ch

Robert Sohn

Woods Hole Oceanographic Institution
360 Woods Hole Rd.
Woods Hole, MA 02543, USA
rsohn@whoi.edu

Barbara John

University of Wyoming
1000 E. University Ave.
Laramie, WY 82071, USA
bjohn@uwyo.edu

Anna-Louise Reysenbach

Portland State University
1719 SW 10th Ave.
Portland, OR 97201, USA
reysenbacha@pdx.edu

Gianreto Manatschal

Ecole et Observatoire des Sciences de la Terre-
Université Louis Pasteur (EOST-UPL)
1 Rue Blessig
67084 Strasbourg, France
manatschal@illite.u-strasbg.fr

DATES AND VENUE

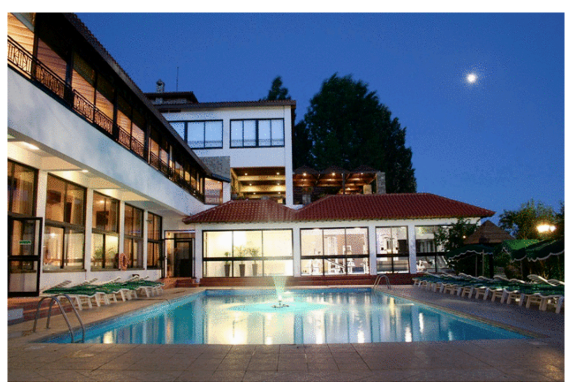
May 8th-15th, 2010.

Rodon Hotel, Agros, Cyprus.

http://www.rodonhotel.com


Agros village, Cyprus (view from the Conference venue)



Views of the Chapman Conference venue, Rodon Hotel

PARTICIPANTS

86 Participants, including 18 students and 8 postdoctoral researchers.

1. **Abe, Natsue**
JAMSTEC, Japan
abenatsu@jamstec.go.jp

2. **Ableson, Meir**
Geological Survey of Israel
meira@gsi.gov.il

3. **Achenbach, Kay**
Durham University, UK
kay.achenbach@durham.ac.uk

4. **Agnon, Amotz**
Hebrew University, Israel
amotz@huji.ac.il

5. **Andreani, Muriel**
ENS - Université de Lyon, France
muriel.andreani@univ-lyon1.fr

6. **Baines, Graham**
University of Adelaide, Australia
graham.baines@adelaide.edu.au

7. **Boulart, Cedric**
CNRS-LMTG, France
cedric.boulart@googlemail.com

8. **Bronner, Adrien**
University of Strasbourg, France
adrien.bronner@etu.unistra.fr

9. **Buck, W. Roger**
LDEO of Columbia University, USA
buck@ldeo.columbia.edu

10. **Canales, Juan Pablo**
Woods Hole Oceanographic Inst., USA
jpcanales@whoi.edu

11. **Cann, Johnson**
University of Leeds, UK
j.cann@see.leeds.ac.uk

12. **Cannat, Mathilde**
CNRS-IPGP, France
cannat@ipgp.fr

13. **Canovas, Peter**
Arizona State University, USA
pcanovas@asu.edu

14. **Casey, John**
University of Houston, USA
jfcasey@uh.edu

15. **Castelain, Teddy**
University of Leeds, UK
eetc@leeds.ac.uk

16. **Charalambous, Maria**
Cyprus Geological Survey
mcharalambous@gsd.moa.gov.cy

17. **Cheadle, Michael**
University of Wyoming, USA
cheadle@uwyo.edu

18. **Choi, Eunseo**
LDEO of Columbia University, USA
echoi@ldeo.columbia.edu

19. **Christofferson, Christian**
University of Wyoming, USA
cchris31@uwyo.edu

20. **Cole, Elizabeth**
University of Wyoming, USA
ecole3@uwyo.edu

21. **Constantinou, Costas**
Cyprus Geological Survey
cconstantinou@gsd.moa.gov.cy

22. **Dannowski, Anke**
IFM – GEOMAR, Germany
adannowski@ifm-geomar.de

23. **Delacour, Adelie**
OMP-Univ. Paul Sabatier, France
delacour@dtp.obs-mip.fr

24. **Denny, Alden**
University of Washington, USA
Dennya@u.washington.edu

25. **Ebert, Yael**
Stanford University, USA
yebert@stanford.edu

26. **Escartin, Javier**
CNRS – IPGP, France
escartin@ipgp.fr

27. **Eleftheriou, Eleftheria**
eleftheria.e@gmail.com

28. **Fontaine, Fabrice**
IPGP-CNRS, France
fontaine@ipgp.jussieu.fr

29. **Frueh-Green, Gretchen**
ETH Zurich, Switzerland
frueh@erdw.ethz.ch

30. **Garzetti, Fabio**
University of Pavia, Italy
fabio.garzetti@dst.unipv.it

31. **Georgiou-Morisseau, Eleni**
Cyprus Geological Survey
emorisseau@gsd.moa.gov.cy

32. German, Christopher
Woods Hole Oceanographic Inst., USA
cgerman@whoi.edu

33. Godard, Marguerite
CNRS - Universite Montpellier, France
Marguerite.Godard@um2.fr

34. Granot, Roi
IPGP, France
granot@ipgp.fr

35. Grimes, Craig
Mississippi State University, USA
cgrimes@geosci.msstate.edu

36. Hadjigeorgiou, Christodoulos
Cyprus Geological Survey
chadjigeorgiou@gsd.moa.gov.cy

37. Hadjigeorgiou, Giorgos
Cyprus Geological Survey
ghadjigeorgiou@gsd.moa.gov.cy

38. Hansen, Lars
University of Minnesota, USA
hanse983@umn.edu

39. Harigane, Yumiko
Kanazawa University, Japan
harigane@staff.kanazawa-u.ac.jp

40. Hellebrand, Eric
University of Hawaii, USA
ericwgh@hawaii.edu

41. Henig, Ashlee
Scripps Institution of Oceanography, USA
ahenig@ucsd.edu

42. Hurst, Stephen
University of Illinois, USA
shurst@uiuc.edu

43. Ildefonse, Benoit
CNRS - Université Montpellier 2, France
benoit.ildefonse@um2.fr

44. Joens, Niels
University of Bremen, Germany
njoens@uni-bremen.de

45. John, Barbara
University of Wyoming, USA
bjohn@uwyo.edu

46. Karson, Jeffrey
Syracuse University, USA
jakarson@syr.edu

47. Katsouris, Philippos
Cyprus Geological Survey
pkatsouris@gsd.moa.gov.cy

48. Katzir, Yaron
University of Wisconsin, USA
yaron@geology.wisc.edu

49. Kelemen, Peter
Columbia University, USA
peterk@ldeo.columbia.edu

50. Kelley, Debbie
University of Washington, USA
kelley@ocean.washington.edu

51. Klein, Frieder
Woods Hole Oceanographic Inst., USA
fklein@whoi.edu

52. Konstantinou, Alexandros
Stanford University, USA
akonstan@stanford.edu

53. Kurz, Mark
Woods Hole Oceanographic Inst., USA
mkurz@whoi.edu

54. Lasseigne, Amy
Rice University, USA
ael3@rice.edu

55. Lilley, Marvin
University of Washington, USA
lilley@u.washington.edu

56. Little, Crispin
Univeristy of Leeds, UK
c.little@see.leeds.ac.uk

57. Loocke, Matthew
University of Houston, USA
mloocke@gmail.com

58. Ma, Changqian
China University of Geosciences, China
cqma@cug.edu.cn

59. MacLeod, Christopher
Cardiff University, UK
macleod@cardiff.ac.uk

60. Maffione, Marco
Instituto Nazionale di Geofisica e Vulcanologia, Italy
marco.maffione@ingv.ir

61. Manatschal, Gianreto
IPGS-EOST, France
manatschal@illite.u-strasbg.fr

62. McCaig, Andrew
University of Leeds, UK
A.M.McCaig@leeds.ac.uk

63. Morishita, Tomoaki
Kanazawa University, Japan
moripta@kenroku.kanazawa-u.ac.jp

64. Morris, Antony
University of Plymouth, UK
amorris@plymouth.ac.uk

65. Nicolaides, Stelios
Cyprus Geological Survey
snicolaides@gsd.moa.gov.cy

66. Ohara, Yasuhiko
Hydrographic and Oceanograph Department of Japan
ohara@jodc.go.jp

67. Olive, Jean-Arthur
MIT / WHOI Joint Program, USA
jaolive@mit.edu

68. Perner, Mirjam
University of Hamburg, Germany
mirjam.perner@uni-hamburg.de

69. Picazo, Suzanne
Institut de Physique du Globe, France
picazo@ipgp.jussieu.fr

70. Plissart, Gaëlle
University of Nantes (LPGN), France
gplissar@ulb.ac.be

71. Pressling, Nicola
University of Southampton, UK
n.j.pressling@soton.ac.uk

72. Reston, Timothy
University of Birmingham, UK
t.j.reston@bham.ac.uk

73. Reysenbach, Anna
Portland State Univ., USA
reysenbacha@pdx.edu

74. Rona, Peter
Rutgers University, USA
rona@marine.rutgers.edu

75. Rough, Mikaella
University of Minnesota, USA
mikaella.rough@gmail.com

76. Sanfilippo, Alessio
Università di Pavia, Italy
alessio.sanfilippo@dst.unipv.it

77. Sawyer, Dale
Rice University, USA
dale@rice.edu

78. Schouten, Hans
Woods Hole Oceanographic Inst., USA
hschouten@whoi.edu

79. Searle, Roger
Durham University, UK
r.c.searle@durham.ac.uk

80. Sohn, Robert
Woods Hole Oceanographic Inst., USA
rsohn@whoi.edu

81. Tivey, Maurice
Woods Hole Oceanographic Inst., USA
mtivey@whoi.edu

82. Tominaga, Masako
Woods Hole Oceanographic Inst., USA
mtominaga@whoi.edu

83. Tsiolakis, Efthymios
Cyprus Geological Survey
etsiolakis@gsd.moa.gov.cy

84. Tucholke, Brian
Woods Hole Oceanographic Inst., USA
btucholke@whoi.edu

85. Xu, Min
MIT-WHOI Joint Program, USA
minxu@mit.edu

86. Zomeni, Zomenia
Cyprus Geological Survey
zzomeni@gsd.moa.gov.cy

Group photo, Agros, Cyprus (next page), in alphabetical order: AA: A. Agnon; AB: A. Bronner; AD: A. Delacour; ADa: A. Dannowsky; ADe: A. Denny; AH: A. Hennig; AK: A. Konstantinou; ALR: A.-L. Reysenbach; AM: A. McCaig; AS: A. Sanfilippo; BI: B. Ildefonse; BJ: B. John; BT: B. Tucholke; CB: C. Boulart; CC: C. Christofferson; CG: C. Grimes; CJM: C. J. MacLeod; CL: C. Little; CM: C. Ma; EC: E. Cole; ECh: E. Choi; EH: E. Hellebrand; FF: F. Fontaine; FG: F. Garzetti; FK: F. Klein; GB: G. Baines; GFG: G. Fruh-Green; GP: G. Plissart; HS: H. Schouten; JAO: J.-A. Olive; JC: J. Casey; JE: Javier Escartin; JPC: J. P. Canales; JRC: J. R. Cann; KA: K. Achenbach; LH: L. Hansen; MA: Muriel Andreani; MC: M. Cannat; MCh: M. Cheadle; MG: M. Godard; ML: M. Lilley; MLo: M. Loocke; MM: M. Maffionne; MP: M. Perner; MR: M. Rough; MT: M. Tivey; MTo: M. Tominaga; MX: M. Xu; NA: N. Abe; NJ: N. Joens; NP: N. Pressling; PC: P. Canovas; PK: P. Kelemen; PR: P. Rona RB: R. Buck; RCS: R. Searle; RG: R. Granot; RS: R. Sohn; SH: S. Hurst; SP: S. Picazo; TC: T. Castelain; TM: T. Morris; TMo: T. Morishita; TR: T. Reston YE: Y. Ebert; YH: Y. Harigane; YK: Y. Katzir; YO: Y. O'hara. Rest of attendees not in the photo are listed above.


AK
RG
AB
CB
JC
NJ
CC
RCS
MC
AM
GB
ALR
TM
BT
CJM
FK
MT
KA
AD
ADe
LH
BJ

SCIENTIFIC PROGRAM

Saturday, 8 May

17:00-19:30h *Apollon Room*	**Registration**
19:30h *Rodon Restaurant*	**Dinner**

Sunday, 9 May

07:00-08:30h *Rodon Restaurant*	**Breakfast**
08:30-09:00h *Apollon Room*	**Introduction to Conference – J. P. Canales & J. Escartín**
09:00-09:45h *Apollon Room*	**Morris, Anthony** "Palaeomagnetic Insights Into Oceanic Detachment Fault Processes at Mid-ocean Ridges"
09:45-10:30h *Apollon Room*	**McCaig, Andrew** "Hydrothermal Systems and Detachment Faulting"
10:30-11:00h *Rodon Cafateria*	**Coffee Break & Registration**
11:00-11:45h *Apollon Room*	**Früh-Green, Gretchen** "Serpentinization of the Oceanic Lithosphere: Consequences for Hydrothermal Activity and Biogeochemical Cycles"
11:45-12:30h *Apollon Room*	**Perner, Mirjam** "Microbial communities and metabolisms from basalt-and ultramafic-hosted vents"
12:30-14:00h *Rodon Restaurant*	**Lunch Break**
14:00-15:30h *Apollon Room*	**Introduction to Field Trip 1 – J. Cann & C. MacLeod**
15:30-16:00h *Rodon Cafateria*	**Coffee Break**
16:00-19:30h *Apollon & Athina Rooms*	**Poster Session I**
19:30h *Rodon Restaurant*	**Dinner**

Monday, 10 May

07:00-08:30h *Rodon Restaurant*	**Breakfast**
08:30-18:00h	**Field Trip 1: Introduction to the Troodos Ophiolite**
18:00-19:30h *Apollon & Athina Rooms*	**Poster Session I**

19:30-20:30h *Rodon Cafateria*	**Poster Reception**
20:30h *Rodon Restaurant*	**Dinner**

Tuesday, 11 May

07:00-08:30h *Rodon Restaurant*	**Breakfast**
09:00-09:45h *Apollon Room*	**Cannat, Mathilde "**Oceanic Detachment Faults and the Exhumation of Gabbros and Mantle-derived Peridotites at Mid-ocean Ridge"
09:45-10:30h *Apollon Room*	**Kelley, Debbie** "Linkages Among Serpentinization and Life in Ultramafic-hosted Hydrothermal Systems: The Lost City Hydrothermal Field"
10:30-11:00h *Rodon Cafateria*	**Coffee Break**
11:00-11:45h *Apollon Room*	**Sohn, Robert** "Geophysical Constraints on the Structure of Detachment Faults: Stone Cold Facts, Red Hot Topics, and Everything In-between"
11:45-12:30h *Apollon Room*	**Cheadle, Michael** "Fault Rheology, Footwall Deformation and Geochronologic Constraints on the Process of Detachment Faulting at Mid-Ocean Ridges"
12:30-14:00h *Rodon Restaurant*	**Lunch Break**
14:00-14:45h *Apollon Room*	**John, Bobbie** "Oceanic and Continental Detachment Fault Systems: How Similar Are They?"
14:45-15:30h *Apollon Room*	**Manatschal, Gianreto** "The Role of Detachment Faults During Crustal Thinning, Mantle Exhumation and Continental Break-up at Magma-poor Rifted Margins?"
15:30-16:30h *Apollon Room*	**Introduction to Field Trips 2 and 3 – J. Cann & C. MacLeod**
16:30-17:00h *Rodon Cafateria*	**Coffee Break**
17:00-19:30h *Apollon & Athina Rooms*	**Poster Session I**
19:30h *Rodon Restaurant*	**Dinner**

Wednesday, 12 May

07:00-08:30h *Rodon Restaurant*	**Breakfast**
8:30-18:00h	**Field Trip 2** **Group A: Western Limassol Forest** **Group B: Eastern Limassol Forest**

18:00-19:30h *Apollon & Athina Rooms*	**Poster Session II**
19:30h *Rodon Restaurant*	**Dinner**

Thursday, 13 May

07:00-08:30h *Rodon Restaurant*	**Breakfast**
08:30-18:00h	**Field Trip 3** **Group A: Eastern Limassol Forest** **Group B: Western Limassol Forest**
18:00-19:30h *Apollon & Athina Rooms*	**Poster Session II**
19:30h *Rodon Restaurant*	**Dinner**

Friday, 14 May

07:00-08:45h *Rodon Restaurant*	**Breakfast**
08:45-09:00h *Apollon Room*	**Introduction to Breakout Groups**
09:00-10:00h *Apollon, Demetra and Arthemis Rooms*	**Breakout Groups 1A, 1B, 1C to discuss the following:** How and Under Which Conditions Does Detachment-faulting Lead to the Formation and Development of OCCs? What are the Mechanisms and Conditions that Promote and Sustain Strain Localization Over Long Periods of Time, and the Development of an OCC? What are the Similarities and Differences Between Oceanic and Continental Core Complexes? What Can We Learn About Continental Breakup and Initiation of Seafloor Spreading From OCCs?
10:00-10:30h *Apollon Room*	**Panel Discussion**
10:30-11:00h *Rodon Cafateria*	**Coffee Break**
11:00-12:00h *Apollon, Demetra and Arthemis Rooms*	**Breakout Groups 2A, 2B, 2C to discuss the following:** What is the Lithological Structure of OCCs and its Variability at Scales of Meters to Tens of Kilometers? What are the Linkages Between Deformation and Magmatic Emplacement?
12:00-12:30h *Apollon Room*	**Panel Discussion**

12:30-14:00h *Rodon Restaurant*	**Lunch Break**
14:00-15:15h *Apollon Room*	**Kelemen, Peter** "Evaluating In Situ Mineral Carbonation in Near-Seafloor Peridotite for CO_2 Capture and Storage"
15:15-16:30h *Apollon Room*	**Reysenbach, Anna-Louise "**The microbiology of OCC's: Implications for life in the subsurface and elsewhere in the solar system"
16:30-17:00h *Rodon Cafateria*	**Coffee Break**
17:00-19:30h *Apollon & Athina Rooms*	**Poster Session II**
18:30-19:30h *Apollon & Athina Rooms*	**Poster Reception**
19:30h *Rodon Restaurant*	**Dinner**

Saturday, 15 May

07:00-08:30h *Dionysos Restaurant*	**Breakfast**
08:30-09:30h *Apollon, Demetra and Arthemis Rooms*	**Breakout Groups 3A, 3B, 3C to discuss the following:** What Drives Hydrothermal Circulation in OCCs and Detachment Faults? What are the Feedbacks Between Fluid Circulation, Deformation, and Magmatic Processes? What is the Biodiversity and Characteristics of Ecosystems Associated with OCCs, and How are They Related to the Style of Hydrothermal Circulation within OCCs and Along Detachment Faults?
09:30-10:00h *Apollon Room*	**Panel Discussion**
10:00-10:30h *Rodon Cafateria*	**Coffee Break**
10:30-12:30h *Apollon Room*	**Open Discussion, Summary, and Perspectives**

ABSTRACTS

Poster I-1

High Temperature Metamorphism and Petrological Insights of an Abyssal Chromitites From Site 1271, ODP Leg 209, MAR 15 20 N

Abe, Natsue

IFREE, JAMSTEC, Yokosuka, JAPAN

Dunite and gabbroic materials, the rocks compose the moho transition zone, are recovered from 15 20 N FZ, the Mid- Atlantic Ridge (MAR) during (ODP) Leg 209. Several podiform chromitites were recovered at Site 1271, both Hole 1271A and B, south of 15 20 N FZ during the cruise. The primary chromites in the chromitites have moderately high-Cr# (0.52 and 0.48 for Hole 1271A and 1272B, respectively) and chromian spinels in the surrounding chromitites have similar composition. It is considered that podiform chromitite is formed by two kind of melt (melt-mantle interaction, therefore there should be plenty volume of melt in the mantle beneath this area. Abundant of gabbro and dunite were recovered from this area suggest that main volume of melt body were consumed in the upper mantle by melt-wallrock interaction. On the other hand, chromite grains have thick rims of Cr-magnetite or completely replaced by magnetite without chromite core. Cr content elevation in the Cr-magnetite rim occurred with Fe-enrichment. These chemical modifications suggest that the chromitite from Site 1271 were metamorphosed at amphibolite facies because significant Al-missing from chromite cores is taken place above 550 degree Celsius.

Poster II-41

Lithosphere Accretion and the Deepest Roots of Detachment Faults: Evidence from Abyssal Peridotites Beneath Atlantis Bank, SWIR

Achenbach, Kay L.; Cheadle, Michael J.; Dick, Henry J.; Swapp, Susan M.

K.L. Achenbach, Department of Earth Sciences, Durham University, Durham, UNITED KINGDOM; M.J. Cheadle, S.M. Swapp, Department of Geology & Geophysics, University of Wyoming, Laramie, WY; H.J. Dick, Geology & Geophysics Department, Woods Hole Oceanographic Institution, Woods Hole, MA

The deformation conditions in the uppermost mantle beneath the roots of a mid-ocean ridge detachment fault are not well understood. Here we use abyssal peridotites from the footwall of a detachment fault to investigate the latest stages of the lithospheric accretion at an oceanic core complex. Twelve spinel lherzolites were collected using the Kaiko unmanned submersible along a single 1.5-km dive track on the western flank of the Atlantis Bank oceanic core complex adjacent to the Atlantis II Transform, south of the Southwest Indian Ridge (SWIR). All samples were examined petrographically; nine were analyzed for crystal lattice-preferred orientation (LPO) using electron backscatter diffraction (EBSD), and two were analyzed for clinopyroxene trace element compositions. All the samples are protogranular to coarse porphyroclastic in texture, and are thus typical of mantle rocks deformed in the asthenosphere. LPO data support this interpretation, as the LPOs of all constituent minerals are fairly weak (olivine M-index = 0.05–0.14; orthopyroxene M-index = 0.05–0.14; clinopyroxene M-index = 0.04–0.07). Furthermore, olivine LPOs preserve slip in the (010)[100] system, which is characteristic of the high-temperature, low-stress, low-water-content deformation expected beneath mid-ocean ridges. Statistically significant differences in LPO strength imply variations in degree of mantle deformation. The rocks preserve melt-rock interaction textures that are essentially undeformed, and the prevalence of these melt-related features varies from rock to rock and is not related to variations in LPO strength. Plagioclase is absent in the peridotites, and spinel is present in some melt-related features. Textures preserved in the peridotites show varying degrees of post-deformation melt-rock interaction. The available trace element data also suggest variable amounts of melt-rock interaction; the slightly more enriched clinopyroxene grains are found in the sample with the greatest textural evidence for melt-rock interaction, and the more depleted grains are found in the sample with the least textural evidence for melt-rock interaction. Thus, the Atlantis Bank peridotites reveal a history of heterogeneous deformation during the latest stages of asthenospheric upwelling.

The last stages of deformation in these rocks occurred at temperatures of 1100oC or more, at the lithosphere-asthenosphere boundary. This deformation was subsequently overprinted by melt-rock interaction at depths of ~25km or greater (based on published thermal models). Thus, at the time that deformation localized into discrete shear zones of the detachment fault, mantle deformation was already somewhat heterogeneous on the scale of hundreds of meters and melt was still actively percolating through the mantle.

Poster I-8

Tectonic Structure and Internal Composition of the Rainbow Massif, Mid-Atlantic Ridge 36°14'N

Andreani, Muriel; Ildefonse, Benoit; Delacour, Adelie; Escartin, Javier; Godard, Marguerite; Dyment, Jerome

M. Andreani, LST, ENS - Université Lyon 1, Lyon, FRANCE; B. Ildefonse, M. Godard, GM, CNRS- Université Montpellier 2, Montpellier, FRANCE; A. Delacour, DTP, OMP-Université Paul Sabatier, Toulouse, FRANCE; J. Escartin, J. Dyment, IPGP, CNRS, Paris, FRANCE

The ultramafic-hosted Rainbow hydrothermal field is located on a massif at a non-transform offset between the AMAR and South AMAR ridge segments, at 36°14'N along the Mid-Atlantic Ridge (MAR). This massif shares some characteristics with other oceanic core complexes (OCCs), like the common dome morphology, although no corrugated surface has been observed so far. During the two MoMARDREAM cruises (in July 2007 on R/V Pourquoi Pas ? and in Aug-Sept 2008 on R/V Atalante), we studied the structural context of the hydrothermal system and the lithology of the massif. Hydrothermal and basement rock samples were recovered by dredging and diving (with the manned submersible Nautile and the ROV Victor), complementing prior sampling realized during the FLORES (1997) and IRIS (2001) cruises. The tectonic of the Rainbow Massif is dominated by a N-S trending fault pattern on its western flank and a series of SW-NE fault-related ridges crosscutting the massif. Available focal mechanisms indicate that tectonic extension is perpendicular to N30-50° trending-direction. The active high-temperature hydrothermal system is located in the area were these two systems crosscut. Mantle peridotites (spinel harzburgites and dunites) were the predominant rock type recovered at the footwall and show petrographic characteristics of both melt-rock and fluid-rock interaction. Melt-rock interaction is evidenced by typical interstitial texture and high REE concentrations (1 x Chondrite). Variable degrees and styles of serpentinization and deformation (commonly undeformed or displaying talc-serpentine foliated schist into faults) were identified in the hydrated peridotites. Serpentinites are frequently oxidized and can be highly enriched in iron oxide veinlets, also indicated by the high FeO contents of some samples. In addition to ultramafic rocks, gabbros, cm- to dm-thick gabbroic veins, and basalts (including fresh glass) were recovered from talus and sediments on the SW and NE massif flanks. Massive chromitite was also recovered in one dredge haul. The inferred lithological variability of the Rainbow massif footwall is thus consistent with that of OCCs studied along the MAR and Southwest Indian Ridge. The stockwork of the hydrothermal system has been sampled on two locations on the western side of the present-day hydrothermal field, along N-S trending normal fault scarps and within the talus underneath. It is mainly made of massive sulfides, strongly altered serpentinites, and breccias containing clasts of iron sulfide and/or iron oxide impregnated serpentinites. Our preliminary interpretation indicates that the Rainbow massif has been exhumed by tectonic extension, but this tectonic context is much more complex than that of other well-studied OCCs. The massif is located within a non-transform offset and does not develop in continuity with the crust accreted along one flank of the ridge axis. This context would explain the obliquity of both the cross-cutting faults and the focal mechanisms and the lack of evidence of single detachment fault responsible for the exhumation of the massif.

Poster I-9

The Tectonic Setting and Evolution of the Atlantis Bank Oceanic Core-complex

Baines, Graham; Schwartz, Joshua J.; Cheadle, Michael J.; John, Barbara

E.G. Baines, School of Earth & Environmental Sciences, University of Adelaide, Adelaide, South Australia, AUSTRALIA; J.J. Schwartz, Department of Geological Sciences, Alabama, Tuscaloosa, AL; M.J. Cheadle, B.E. John, Department of Geology and Geophysics, University of Wyoming, Laramie, WY

Atlantis Bank on the southwest Indian Ridge (SWIR) formed 10-13 Ma by oceanic detachment faulting. Oceanic detachment faults are scarce in the immediate vicinity, leading us to suggest that detachment faulting at Atlantis Bank was triggered by a short-lived regional increase in the full-spreading rate along the SWIR and was preferentially localized adjacent to the Atlantis II Transform Fault, whose growth since at least 30 Ma was accommodated by long-lived asymmetric spreading and was under transtension ~8-20 Ma. Once detachment faulting commenced, spreading was highly asymmetric such that the detachment fault formed the principal plate boundary. U-Pb zircon dating suggests that the lithosphere was up to 18-km-thick and that magmatism continued relatively unabated. However, crustal accretion was focused at depth in the footwall of the fault leading to relatively enhanced accretion of the lower crust and reduced volcanism in the axial valley. The 1.5 km lower crustal section in ODP Hole 735B accreted rapidly, and cooled to below 365°C in <0.5 Ma, but anomalously young thermochronologic ages suggest later heating by hydrothermal circulation along fault zones at ~8-9 Ma. These results require a tectonothermal event that significantly post-dates detachment faulting. This event and the faulting which uplifted Atlantis Bank to sea-level were likely related to tectonics along the Atlantis II Transform, and specifically to the final stages of long-lived transtension caused by a rotation in the direction of plate-spreading 19.6 Ma.

Poster I-21

Refraction Constraints on 2~5 km Subseafloor Depths, Atlantis Massif MAR 30°N

Blackman, Donna K.; Collins, John A.

D.K. Blackman, IGPP, Scripps Institution Oceanography, La Jolla, CA; J.A. Collins, MGG, Woods Hole Oceanographic Institution, Woods Hole, MA

The seismic structure of the oceanic core complex comprising Atlantis Massif, 30°N on the Mid-Altantic Ridge, is assessed through analysis of OBS refraction data. The source-receiver geometry for a 1997 experiment provides coverage that extends to 4-8 km subseafloor depths. For assessing the depth to mantle velocities, a 40-km cross-axis line is most relevant; we have also considered 2 shorter along-strike lines over the central and southern parts of the domal core. Velocity structure results are based on inversion of first arrival travel-times and we have tested robustness via a suite of contrasting starting models where initial Moho depth is varied (3-6 km subseafloor). The OBS data alone require near-seafloor (< 0.5-1 km) high velocity gradients within the Central Dome and upper km structure that is similar to that determined from much denser multi-channel seismic refraction modeling. No clear PmP or Pn arrivals that would mark a strong contrast across a sharp Moho have been identified in the data. Modeling all arrivals as Pg, there is no requirement that mantle velocities be very shallow (< 3 km) anywhere along the lines. However, velocities > 7.5 km/s are determined to occur at depths of 4-5 km on the inside corner lithosphere. This indicates that the crust mantle interface is shallower than normal beneath the OCC and this finding is consistent with inferences based on prior 3-D gravity modeling. In contrast, the depths determined for material > 7.5 km/s (essentially fresh, olivine dominated rock which would likely be of mantle origin) in both the axial zone and the outside corner appear to be deeper, and likely typical for young Atlantic crust. One of the along-strike lines provides the first velocity information on the western portion of the Southern Ridge. Initial inversions suggest that velocities and gradients there are somewhat lower than those determined previously for the central portion of the Southern Ridge (Canales et al., 2008; also corroborated in our coarser refraction coverage) and signficantly lower than recently determined (Henig et al., 2009) for the eastern portion of this part of the domal core of Atlantis Massif.

Poster II-69

Emerging Technologies for in Situ Dissolved Methane Measurements in Hydrothermal Vents

Boulart, Cedric C.; Chavagnac, V.; Seat, H. C.; Cattoen. M.; Bosch, Th.; Arguel, Ph.; Dubreuil, B.; Aufray, M.; Behra, Ph.; Castillo, A.; Gisquet, P.

C. Boulart, V. Chavagnac, A. Castillo, P. Gisquet, LMTG-CNRS-UPS-IRD, Toulouse, FRANCE; H. C. Seat, M. Cattoen, Th. Bosch, LOSE-ENSEEIHT, Toulouse, FRANCE; Ph. Arguel, LAAS-CNRS, Toulouse, FRANCE; B. Dubreuil, Ph. Behra, LCA-INPT-ENSIACET, Toulouse, FRANCE; M. Aufray, CIRIMAT - INPT-ENSIACET, Toulouse, FRANCE

Hydrothermal systems along mid-ocean ridges are a significant source of methane for the Deep Ocean, which can be related to different geochemical processes (e.g. Lein et al. 2000; Charlou et al. 2002). Among them, serpentinization can produce high methane concentrations in hydrothermal fluids and strongly impact the gas flux to the water column. However dissolved gas and fluid fluxes are notoriously difficult to measure, leading to inaccuracies in the estimate of the amount of methane produced by hydrothermal systems. Moreover, significant uncertainties exist on the distribution and the patchiness of the marine sources. These issues can be addressed by in situ chemical sensing to gain new insights on the geographical distribution of the vents and on the time variation of geochemical processes at hydrothermal sources. Different sensing technologies and sensors currently exist but suffer from limitations (time response, hysteresis, (Boulart et al., In Press), which can be bypassed by optical methods associated to "intelligent" polymers. It is shown that dissolved methane can be detected and accurately measured by a surface plasmon resonance sensor associated with a methane specific binding polymer (Boulart et al. 2008). We describe a new detector based on this property, using optical fibres and infrared detection. Tests of detection and calibrations are performed in the laboratory under different environmental conditions (temperature, pressure, pH). Responses of the methane specific polymer are also studied with respect of the same conditions. We present here the first results from the laboratory-based experiments.

Poster II-75

Magnetic Anomalies in the Ocean-continent Transition Zone from the Iberian-Newfoundland Margins : An Alternative View

<u>Bronner, Adrien</u>; Sauter, Daniel; Manatschal, Gianreto; Munschy, Marc

Institut de Physique du Globe, Strasbourg, FRANCE

Some of the magnetic anomalies from the deepest part of the Iberian-Newfoundland margins have been interpreted as seafloor spreading anomalies. M0 up to M22 magnetic anomalies have been identified in the zone of exhumed mantle within the ocean-continent transition. This interpretation is strongly debated. The magnetic anomalies are often weak, and there is no agreement about the source. Either gabbro bodies or serpentinized peridotites have been proposed to be responsible for these magnetic anomalies. Moreover, kinematic reconstructions using these isochrons have shown to be inconsistent with some geological constraints. Here we propose an alternative model based on forward modeling of magnetic anomaly profiles using seismic refraction and drill hole data. We show that these magnetic anomaly profiles can be explain without inversion of the Earth magnetic field. We use only positive magnetizations assuming that magmatic and tectonic processes occur during the quiet Cretaceous magnetic period. We propose that the main magnetic anomaly (J anomaly) in the ocean continent transition area of the Iberian-Newfoundland margins might be explained by underplated magmatic bodies and surface lava flows. These magmatic bodies and lavas may result from the magmatic and tectonic event which marks the transition to seafloor spreading.

Poster II-62

Magmatic Influences on Axial Relief and Oceanic Core Complex Formation

<u>Buck, W. Roger</u>; Choi, Eunseo

Lamont-Doherty Earth Obs., Columbia Univ, Palisades, NY

Observations indicate that slow spreading ridges operate in several modes including the formation of core complexes and simple models reproduce these modes. Mid-ocean ridges also show a continuous variation in across-axis bathymetric relief from axial highs to deep axial valleys. However, models that fix the fraction of plate separation accommodated by magma (M) cannot explain the observed range of axial depths. For M=1 the axial depth is controlled by the density structure (or buoyancy) of the axis and so we term this depth, Dbuoy. If M < 1 the axial valley depth is equivalent to the depth produced by tectonic stretching alone (here termed Dstretch). A resolution to this problem may come from consideration of magma input on a segment scale. Assuming that most dikes are fed from a magma chamber at a segment center allows simulation of how magma might be distributed with distance from the center. At a given distance from a segment center we then fix calculate the magma input into 2D cross-sectional numerical models of spreading that treat faulting and dike intrusions in a mechanically consistent way. In these models dikes open in response to the lithospheric stress field after a set time of spreading with no dikes. The amount of magma delivered into the a given cross section depends on the extensional stresses there and this in turn depends partly on the depth of the spreading axis. The deeper the axis the larger the extensional stresses so that more magma is pulled into the that area. Though the model results depend on several parameters, including the time interval between dike events, the axial lithospheric thickness and the magma source pressure-volume relation, the main result is simple. Since the magma input depends on the axial depth a complete range of axial depths is possible. The deeper the axis the more magma is supplied to dikes in an event. As long as M<1 the axis will deepen, but M should increase with increasing axial depth. If M=1 the axis will cease deepening. If the is no depth where magma volumes are sufficient to accommodate all spreading then the axial depth equals Dstretch. Large offset faults only form for M<1 cases when the axis is at its maximum depth.

Poster I-19

Advanced Seismic Imaging of Oceanic Core Complexes

Canales, Juan Pablo

Woods Hole Oceanographic Institution, Woods Hole, MA

Oceanic lithosphere formed along slow- and ultra-slow spreading centers is highly heterogeneous at many different scales. This compositional and structural heterogeneity arises from temporal and spatial variations in mantle composition and thermal structure, magma supply, efficiency of melt extraction, tectonic extension, or a combination of any of these factors. This heterogeneity is well exposed at oceanic core complexes (OCCs), which are deep sections of the oceanic lithosphere exhumed to the seafloor by long-lived detachment faults. Deep drilling at OCCs thus offers a unique opportunity to sample the lower crust and upper mantle of slow-spreading lithosphere. However, the importance of the geological processes inferred from the one-dimensional view that deep drilling provides can only be assessed by understanding the complex, three-dimensional structure of OCCs. Seismic reflection and refraction are powerful methods to image the deep structure of OCCs at several scales and depths. Here we present advances made during the last two years on seismic imaging of OCCs along the flanks of the Mid-Atlantic Ridge. Travel-time tomography of long-offset (6 km) multichannel seismic data reveals the heterogeneity of the shallow (<1.5 km) structure of OCCs at scales of a few to tens of kilometers, while waveform tomography has the potential to image the internal structure of OCCs at scales comparable to those of seafloor observations.

Poster II-51

Oceanic Core Complexes in the Mid-Atlantic Ridge for 200 km South of the Kane Fracture Zone

Cann, Johnson R.; Smith, Deborah; Escartin, Javier; Schouten, Hans

J.R. Cann, School of Earth and Environment, University of Leeds, Leeds, UNITED KINGDOM; D. Smith, H. Schouten, Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA; J. Escartin, Groupe de Geosciences Marines, CNRS-IPGP, Paris, FRANCE

Recent surveys of the Mid-Atlantic Ridge have identified bathymetric features that distinguish the different tectonic elements that make up the oceanic crust (Smith et al., 2008). Fault-dominated regions show a blocky topography consisting of domal core complexes that are often corrugated, symmetrical linear ridges with steep outward- and inward-facing slopes and oval basins on the outward side of the ridges. We interpret the domal core complexes as exposures of long-lived detachment faults that have been rotated to low angles as they emerge, and the linear ridges as highly rotated fault blocks with the steep outward facing slopes representing volcanic seafloor that was erupted originally close to horizontal in the median valley floor. Sampling of serpentinite, gabbro and metabasalt is common in fault-dominated regions. Magmatic-dominated segments show linear ridges with steep inward-facing scarps and well-preserved volcanic features such as cones and terraces. We interpret these as slices of the median valley floor uplifted by faulting, but scarcely rotated. The axes of the volcanic ridges are commonly curved towards segment ends. Plutonic rocks are not recovered from magmatic segments. The axis of the median valley floor always shows a volcanic morphology; the differences develop at the edges of the median valley and on its walls. We apply these new criteria to a reanalysis of a well-surveyed area of the Mid-Atlantic Ridge running south for over 200 km from the Kane Fracture Zone and reaching out more than 100 km (about10 Ma) on each side. The area covers about 50,000 km2 of Atlantic Ocean floor. The segmentation of this area was first studied by Gente et al. (1995), who showed that the pattern of segmentation is complex, with spreading segments apparently growing and shrinking on times scales of around 1 Ma. Our analysis shows that within this area about half of the ocean floor carries the fault-dominated signal. Along the 205 km of active spreading axis, five spreading segments can be identified. Of these one (35 km long) is spreading magmatically on both flanks, while the other four are spreading by faulting on one flank and magmatically on the other. This indicates that at present about 40% of the new ocean lithosphere generated in this area is fault-dominated.

References:

Gente et al.,1995, Characteristics and evolution of the segmentation of the Mid Atlantic Ridge between 20° and 24°N during the last 10 million years. Earth and Planetary Science Letters, 129, 55-71.

Smith, et al., 2008, Fault rotation and core complex formation: Significant processes in seafloor formation at slow-spreading mid-ocean ridges (Mid-Atlantic Ridge, 13_–15°_N): Geochemistry, Geophysics, Geosystems, v. 9, p. Q03003, doi:10.1029/2007GC001699.

Oral – Tuesday 11th, 09:00

Oceanic Detachment Faults and the Exhumation of Gabbros and Mantle-derived Peridotites at Mid-ocean Ridges

Cannat, Mathilde

Equipe de Géosciences Marines, CNRS-UMR7154, Institut de Physique du Globe, 4 place Jussieu 75252 Paris Cedex 05 FRANCE

Serpentinized peridotites and gabbros are exposed over roughly 25% of the seafloor formed at the slow-spreading Mid-Atlantic Ridge (MAR), and up to 50% of the seafloor formed in magma-starved regions of ultraslow ridges. Large vertical displacements along axial normal faults are required to exhume these deeply-derived rocks. In this presentation, I will give an overview of the geological-geophysical observations made in ultramafic seafloor areas of the MAR and Southwest Indian Ridge (SWIR). These observations indicate that corrugation-bearing Oceanic Core Complexes are but a particular case of axial exhumation structure, probably forming in conditions of intermediate magmatic activity. This raises the issue of the extent to which observations made on corrugated, or un-corrugated, exhumation faults can be used to constrain generalized models of oceanic detachments and their evolution. Another issue that is often left aside in conceptual models of oceanic detachment faults, is that of the concomittant deformation in the lower, ductile part of the axial lithosphere. I will discuss these two issues, trying to outline end-member hypotheses, and their possible consequences in terms of lithospheric architecture.

Poster II-52

Lateral and Temporal Variations in the Degree of Mechanical Weakening in the Footwall of Oceanic Detachment Faults

Cannat, Mathilde; Escartin, Javier; Lavier, Luc; Picazo, Suzanne Marie; Sauter, Daniel

M. Cannat, J. Escartin, S. M. Picazo, Géosciences Marines, CNRS-IPGP, Paris Cedex 05, FRANCE; L. Lavier, Jackson School of Geosciences, University of Texas, Austin, TX, United States; D. Sauter, EOST, CNRS-Université de Strasbourg, Strasbourg, FRANCE

The motivation for the work presented in this poster (partially published in Cannat et al., EPSL 2009) is that, although a lot of attention has been rightly given in recent years to mid-ocean ridge detachments that produce corrugations in their footwall, these represent only a few percent of the seafloor formed at slow and ultraslow ridges. These corrugated detachments therefore accommodate only a fraction of the large vertical movements needed to expose serpentinized peridotites and gabbros over roughly 25% of the seafloor formed at the slow-spreading Mid-Atlantic Ridge (MAR), and up to 50% of the seafloor formed in magma-starved regions of ultraslow ridges. In the poster, we show examples of the variability of the relief that is associated WITH exposures of serpentinized peridotites and gabbros formed at both the MAR and the ultraslow Southwest Indian Ridge (SWIR). These examples illustrate two characteristics of corrugated detachments relative to other large offset axial normal faults : their exposed footwall has a very subdued relief when connected to a detachment that is still active on-axis (Smith et al., Nature 2006), but commonly has a prominent relief when found off-axis. The subdued on-axis relief indicates very important flexural rotation over short distances, consistent with extremely low mechanical strength of the fault's footwall (Smith et al., Gcubed 2008), which may also account for the formation of corrugations (Spencer, Geology 1999). The pronounced off-axis relief is taken to indicate that the strength of the fault's footwall increased significantly at the termination stage.

Following Buck (Tectonics 1988), we hypothesize that stresses related to bending of the plate cause internal deformation and damage in the footwall of the fault, which is associated with weakening. As a possible mechanism for enhanced footwall weakening while corrugated surfaces form, we propose the formation of weak shear zones coated with hydrous minerals such as talc, amphibole, chlorite and serpentine, in mantle-derived ultramafics next to gabbro intrusions. If this hypothesis is correct, the amount of footwall weakening and roll-over along axial detachment faults at slow spreading ridges may be controlled both by the distribution of gabbros intrusions in exhumed ultramafics, and by access to hydrothermal fluids in the footwall of the detachment.

Poster I-35

Thermodynamic Constraints on Biomolecule Synthesis and Metabolism Due to Alteration of Ultramafic Host Rock

Canovas, Peter A.; Shock, Everett L.

P.A. Canovas, E.L. Shock, School of Earth and Space Exploration, Arizona State University, Tempe, AZ; E.L. Shock, Department of Chemistry & Biochemistry, Arizona State University, Tempe, AZ

The alteration of igneous basement rocks produces disequilibria that lead to microbial habitat generation in seafloor hydrothermal systems. The evolution of fluid compositions and mineral alteration assemblages constrains the availability of energy for microbes and influences the viability of various metabolic pathways. By combining theoretical models of rock alteration and fluid mixing with biomolecule synthesis and metabolism, a quantitative approach can be taken toward predicting microbial metabolisms as functions of temperature, pressure, fluid composition and the extent of rock alteration. These results can be presented in the form of affinity diagrams where conditions of real systems can be plotted to link the nonequilibrium thermodynamics of water-rock alteration with the nonequilibrium processes of metabolism and biosynthesis. To this end, reaction path modeling was performed on host rock assemblages with representative solid solution compositions of olivine, orthopyroxene and clinopyroxene. Comparisons between assemblages reveal large contrasts in dissolved hydrogen, silica, and pH. Dissolved hydrogen concentrations in particular change dramatically in response to small changes in the initial mineral assemblages, with large variations centered around host rocks dominated by olivine. In a biochemical/synthesis context, the results suggest that energy supply and demand will be modulated by a variety of mineral sources of ferrous iron and the diversity of biochemical reactions microorganisms couple to mineral alteration. For instance, in some systems the synthesis of alkanes, alkenes and some carboxylic and amino acids is thermodynamically favored without the input of energy from microorganisms or their need to couple synthesis to other reactions. However, this is almost never the case for energy-intensive biomolecules such as carbohydrates, purines, and pyrimidines (Shock and Canovas, 2010). In order to make these compounds, microorganisms need to couple their syntheses to other reactions. In many hydrothermal systems the energy released by methanogenesis is more than sufficient for the biosynthesis of nicotinamide dinucleotide (NAD), adenosine triphosphate (ATP), and other biomolecules central to metabolism. Other energetic couplings with respect to biomolecules may be explored as well. For example, under conditions associated with low temperature alteration environments, thermodynamic calculations indicate there is sufficient drive to support the reduction of NAD via hydrolytic oxidation of ferrous minerals. Reactions using ferrosilite to meet energetic demands are more or less favorable than those using fayalite depending on the conditions where they occur. Overall, microbes will meet their energetic demands through various coupled biogeochemical pathways, depending on the details of the system they inhabit. As a consequence, coupled metabolic processes will shape the reaction paths, rates and extents of microbial alteration that various systems undergo, as well as their overall biological productivity and diversity.

Poster II-44

Evidence For High Degrees of Mantle Melting, Yet Extensive Development of Oceanic Core Complexes and Significant Evidence of Low Magmatic Production on the Mid-Atlantic Ridge between 12°-16°N

Casey, John F.; Searle, Roger; MacLeod, Christopher J; Murton, Bramley

J.F. Casey, Earth and Atmospheric Sciences, University of Houston, Houston, TX; R. Searle, Geology Department, Durham University, Cardiff, UNITED KINGDOM; C.J. MacLeod, Geology Department, Cardiff University, Cardiff, UNITED KINGDOM; B. Murton, National Oceanography Center, University of Southampton, Southampton, UNITED KINGDOM

he region between 12°N and 16°N on the Mid-Atlantic is characterized by at least 10 near-axis core complexes exposing ultramafic and gabbroic rocks. We have extended sampling programs from previously surveyed northern regions from 14° to 16°N to four newly discovered core complexes (Smith et. al., 2006) and adjacent ridge segments between 14 and 12°30'N on a cruise of the research vessel James Cook in March-April 2007. We examine the distribution of lithologies sampled in the entire region, the newly discovered core complexes, the ridge and core complex morphotectonics along the segments, and the results of geochemical analysis of basalts, gabbroic rocks and mantle assemblages. Geochemical results from these assemblages may help to explain why the basalt characteristics can show variations symptomatic of high degrees of melting (e.g., low Na 8.0) and why the mantle compositions are among the most strongly depleted along the MOR (also indicating high degrees of melting), yet the evidence of mantle unroofing and a thin magmatic crust persist throughout such a broad area. Integrated studies of major element, trace element, and isotopic variations among basalts, gabbroic rocks and igneous and residual ultramafic rocks in the region indicate that 1) the enriched basalts have positive Ta-Nb anomalies, enriched relative to La and Th, 2) basalts have relatively high SiO2 abundances compared to the global average, 3) basalts show a HIMU isotopic influence, and 4) bulk major element abundances and mineral chemistry in mantle rocks indicate that they are among the most depleted, although variably refertilized, residual mantle assemblages sampled to date along MORs. We suggest that much of the regional variation in major and trace element data, as well as isotopic data and the unusual regional geology (multiple core complexes and ridge morphotectonics) reflecting magma supply can be explained by melting of a sub-axial mantle that contains two end members, one highly depleted and the other enriched. These subaxial mantle components appear to involve ancient recycled ocean crust and lithospheric mantle. We also examine melt entrapment within the mantle lithosphere in the subaxial region and local to regional basalt geochemical variations associated with the core complexes.

Poster I-26

Hydrothermal Fluid Flow in Oceanic Gabbros, IODP Site 1309, Mid-Atlantic Ridge: Strontium and Oxygen Isotopic Data

Castelain, Teddy; McCaig, Andrew; Cliff, Bob; Delacour, Adelie; Fallick, Anthony

T. Castelain, A. McCaig, B. Cliff, School of Earth & Environment, Institute of Geophysics & Tectonics, Leeds, UNITED KINGDOM; A. Delacour, Lab. de Dynamique Terrestre et Planétaire, Toulouse, FRANCE; A. Fallick, SUERC, Glasgow, UNITED KINGDOM

IODP Hole U1309B and D were drilled in the footwall of the Atlantis Massif detachment fault at the Mid-Atlantic Ridge 30°N. The cores are composed of gabbroic rocks interlayered with ultramafic rocks, with basalt/diabase sills in the upper 130 m. The dominant alteration occurred in the greenschist facies and is characterised by amphiboles replacing pyroxenes and formation of corona textures between olivine and plagioclase. At depths > 750 mbsf, alteration is restricted to veins, fractures and lithological contacts. Whole rock oxygen isotope values range from 5.6 ‰ to 1.5 ‰, indicating variable degrees of interaction with seawater at temperatures generally > 250°C. Gabbroic rocks and diabases exhibit a range of Sr isotope ratios from MORB values (0.70261) to intermediate ratios (0.70429), while six serpentinites from < 350 mbsf show seawater-like compositions (0.70687 to 0.70904), compared with MORB compositions deeper in the hole (>1 km). A key question is how fluid with a seawater isotopic signature passed through partially altered gabbros to reach thin ultramafic horizons. Samples of individual minerals and alteration zones have been extracted from thin sections using a microscope-mounted drill. Seawater signature is observed in serpentines and prehnites, as well as in amphibole filling vugs, and corona textures. Intermediate values are seen in amphiboles replacing clinopyroxene and chlorite. Plagioclase usually shows a MORB-like value except when altered to albite at vein contacts. Alteration occurred at temperatures ranging from 250 to 350°C (from calibration curves of Zheng, 1993) except for corona textures for which temperatures are >= 500°C (estimated from Cole and Ripley, 1999). These data suggest that fluid percolating through the gabbros was significantly more radiogenic in strontium than the whole rock analyses might suggest. Where fluid flowed through high flux pathways with little exchange with wall rocks, minerals isotopically similar to seawater were precipitated. Serpentinite layers were altered either by fluid passing along such high flux pathways, or at significantly lower temperatures (200-250°C) than the gabbros, as the estimates from the oxygen isotope ratios suggest.

Oral – Tuesday 11th, 11:45

Fault Rheology, Footwall Deformation and Geochronologic Constraints on the Process of Detachment Faulting at Mid-Ocean Ridges

Cheadle, Michael; Barbara E John

Dept of Geology and Geophysics, University of Wyoming, Laramie, WY

The nature of oceanic detachment faults is just beginning to be understood. These faults may localize in both peridotite and gabbro dominated footwalls, and typically reveal a down-temperature deformation history, culminating in a ubiquitous low-temperature talc-chlorite-tremolite fault schist +/- cataclasite assemblage. However, the high-temperature deformation history seems to vary. In peridotite-dominated footwalls such as at Kane (mid-Atlantic Ridge (MAR)), peridotite mylonites commonly form an anastomosing network of thin (1-2m?) shear zones that extend up to 400m below the principal slip surface exposed at the seafloor. These presumably accommodate the transition from distributed deformation in the upwelling asthenosphere to the brittle deformation associated with detachment fault slip. At the gabbro dominated Atlantis Bank (Southwest Indian Ridge), the detachment fault comprises a 100m thick network of anastomosing shear zones consisting of granulite- to amphibolite-grade gabbro mylonites, overprinted by a narrow zone of brittle deformation with the typical fault rock assemblage of gouge, cataclasite and schist. The concentration of high-temperature strain in Fe-Ti oxide gabbros suggests that the shear zones root into hyper-solidus melt lenses. Additional shear zones occur between 470 and 950m below the fault surface exposed at the seafloor, highlighting that high-temperature deformation can occur throughout the footwall. Some of this deformation shows a reverse sense of shear and is associated with the ~60º of bending associated with unroofing the footwall. Elsewhere, for example at the center of Atlantis Massif (MAR), gabbro-hosted detachment fault zones are much thinner (<10-20m?), and high temperature mylonites are rare. This rarity of gabbro mylonites is expected to be the norm, because of the narrow temperature window for plastic deformation. Typically this window is defined by the solidus of evolved melts (~850°C for oxide bearing gabbros), and the brittle plastic transition of 'dry' plagioclase (~750°C).

There remain fundamental questions as to why large slip detachment faults form. Compelling evidence suggests that detachment faults originate as normal, high-angle axial valley faults. Modeling suggests sustained slip may be partially facilitated by limited magma addition to the hanging wall of the fault. Field observations and lab experiments suggests that fault weakening due to water ingress and the formation of "weak" secondary hydrous minerals including serpentine, chlorite, tremolite and talc may lead to continued slip on existing faults rather than the formation of new faults. Hydration and hence fault weakening likely occurs deeper, at higher temperatures, where evolved gabbros are in contact with peridotite. However, the depth of penetration of the hydrothermal circulation remains a major question. Geochronolologic data confirm the results of geomagnetic studies that show that many oceanic core complexes are formed during periods of significant asymmetric spreading and consequent plate boundary migration, raising the question of whether detachment faults form as a consequence of plate boundary migration or vice-versa. Further, the progressive decrease in age of gabbro intrusions toward the detachment fault termination supports the concept of continuous footwall casting, with gabbros continuously crystallizing in the footwall as the fault slips.

Poster II-63

3D Numerical Models for the Formation of Oceanic and Continental Core Complexes

Choi, Eunseo; Buck, W. Roger

Division of Marine Geology and Geophysics, Lamont-Doherty Earth Observatory, Palisades, NY

Oceanic core complexes (OCCs) appear to be a product of a unique mode of lithospheric extension but also stand on a common mechanical ground with the continental counterparts. Our on-going project is to study the extension of continental lithosphere using a combination of geological observations and modeling. Until recently it has been impractical to consider three-dimensional numerical models of the long-term development of extensional faults. We plan to use a newly developed 3D numerical modeling code to study controls on faulting during oblique continental extension including the role of pluton emplacement in the formation of domal cores of continental core complexes (CCCs). Our efforts will be beneficial to the OCC studies in two ways. The methodology can be applied to OCCs in a straightforward fashion. In particular, the 3D code can be used to explore the thermo-mechanical conditions for the formation of OCCs and to simulate their evolution in time and space. In addition, if new results are successfully acquired from our project on continental lithosphere, contributions will be made for the comparison between OCCs and CCCs in the light of these new findings. In this conference, we will present preliminary models for OCC and CCC formation and attempt to compare them.

Poster I-3

The Igneous Architecture of IODP Hole U1309D: ~10's Meter Scale Units Suggest Accretion by Small Volume Intrusive Events

Christofferson, Christian A.; Cheadle, Michael J.; John, Barbara E.; Grimes, Craig B.

C.A. Christofferson, M.J. Cheadle, B.E. John, Department of Geology and Geophysics, University of Wyoming, Laramie, WY; C.B. Grimes, Department of Geosciences, Mississippi State University, Mississippi State, MS

Gabbroic rocks form a significant part of the footwall of many oceanic core complexes. The decreasing age of these gabbros down dip from the breakaway to the termination of the detachment fault suggests that they are continuously accreted as the detachment fault that bounds the core complex slips (Baines et al., 2008). But how are these large (>1 km diameter) gabbro bodies constructed, and at what scale and frequency is melt added to the magma system? Here we report a detailed lithologic analysis of IODP Hole U1309D drilled into the Atlantis Massif core complex on the Mid-Atlantic Ridge in order to address these questions. We present new, high resolution (1 m scale) downhole diagrams for the three igneous macro units, compiled from observations of the archive halves of the entire core, and refined using other available data including magnetic susceptibility. The core contains mostly gabbro, olivine gabbro and trocolitic gabbro (83.2% total). Oxide gabbro comprises 5.4% of the core and appears intermittently within the larger gabbro bodies. These diagrams show that the thickness of the individual magmatic units is on the order of 1 to a few 10's of meters, significantly smaller than implied by previous lithology diagrams (Blackman et al, 2006). Contacts between many of these units are sharp and thus many of the units are interpreted to result from small injections of melt as opposed to in-situ fractionation. However these units are often cut and disaggregated by later intrusive bodies, and hence it is likely that individual gabbro units were initially somewhat larger. Downhole plots of magmatic fabric dip are consistent with the units having initially been intruded as sills, and subsequently rotated at least ~40-50°, as constrained by paleomagnetic data (Morris et al., 2009). We note that the thickest unit in the core (in macro unit II) is 27 m thick (~20m after correcting for dip) placing an upper limit on the thickness of individual injections. U-Pb zircon dating has shown that macro unit II is older than the overlying macro unit I. Macro unit II was formed during a period of magmatic activity at ~1.24 Ma, whereas macro unit I was intruded around 1.17 Ma with some components intruding macro unit II. This relationship requires that the depth of magma intrusion was not constant but shallowed with time, with macro unit I intruded ~1-1.5 km shallower than macro unit II. Using all available data, we propose the gabbros of Atlantis Massif are composite bodies, formed of ~500 m thick gabbro macro units which grew episodically (~ every 70,000 yrs) by relatively small (1 to a few 10's meters) repeated sill-like injections of melt. We conclude that the magma chamber that formed these gabbros was relatively small at any one time. We argue that these bodies were emplaced at varying depths in the footwall and consequently, if the detachment fault is rooted in the magma chamber, that the depth of detachment faulting may have varied with time.

Poster II-71

Understanding Hydrothermal Fluid Flow Along Oceanic Detachment Faults - Kane Oceanic Core Complex, 23°N Mid Atlantic Ridge

__Cole, Elizabeth__; John, Barbara E.; Cheadle, Michael J.; Teagle, Damon; Banerjee, Neil

E. Cole, B.E. John, M.J. Cheadle, Geology and Geophysics, University of Wyoming, Laramie, WY; D. Teagle, National Oceanography Centre, University of Southampton, Southampton, UNITED KINGDOM; N. Banerjee, Earth Sciences, University of Western Ontario, London, Ontario, CANADA

Hydrothermal fluid flow is implicated in large slip oceanic detachment faults; however, the depth and mechanisms of fluid circulation both along the fault zone and into the footwall remain poorly understood. The Kane Ocean Core Complex (OCC) on the Mid-Atlantic Ridge is cut by two moderate-dip faults, which penetrate the detachment fault surface as exposed at the seafloor. Samples collected during R/V Knorr Cruise 180-2 (Tivey et al., 2004) from these fault scarps provide 600-1200m deep cross-sections through the detachment fault zone and into the footwall, affording a unique opportunity to conduct a detailed study of hydrothermal fluid flow associated with the detachment system. Previous isotopic studies (Sr, Nd, and O) have been used to trace fluid flow through oceanic detachment fault zones, however existing work has focused on whole-rock analyses. In contrast, we are conducting Sr- and O- isotopic studies of mineral separates from samples collected from both peridotite- and gabbro-dominated fault scarps that cut the Kane detachment system, to constrain the highest temperatures of hydrothermal circulation. This study, together with detailed microstructural analysis, will help elucidate the full history of fluid flow in the core complex. Hansen (2007) showed that brittle deformation is localized in the upper reaches of the section (< 200 mbsf), close to the principal slip surface, whereas crystal plastic deformation is distributed as localized shear zones throughout the upper 500m of the footwall. More detailed petrographic examination of the samples will help constrain the down-temperature deformation and metamorphic history of the fault system. It is highly likely that fluid flow was pervasive through zones that experienced the greatest brittle deformation, leading to the highest degrees of mineral alteration and serpentinization. Gabbro and peridotite that host high temperature mylonitic fabrics may have acted as seals to focus this fluid flow. The resulting reaction weakening and generation of minerals including talc and serpentine likely facilitated the protracted history of slip along the detachment fault. Together, the microstructural analysis (including mineral deformation mechanisms and estimated temperatures), and the isotopic data, will quantify fluid-rock ratios and will help constrain the thermal history and depth of fluid flow along and through both peridotite and gabbro-hosted detachment faults.

Poster I-17

Two End-members of Oceanic Core Complex Formation

Dannowski, Anke; Grevemeyer, Ingo; Planert, Lars A.

FD 4 - Geodynamics, Leibniz Institute of Marine Sciences (IFM-GEOMAR), Kiel, GERMANY

Oceanic core complexes (OCC) are predominantly generated at slow- or ultra-slow spreading ridge flanks. Basically they are formed during episodes of limited magma supply and hence rifting dominated spreading, exposing deeper crustal rocks. While geophysical studies show that the general lithology is similar at many OCCs the shallower structures seem to differ strongly. We compare seismic modelling results of two oceanic core complexes along the Mid-Atlantic Ridge (MAR), formed near 5° S and at 22.19° N. They show significant differences within the shallow structures while the deeper structures show similar characteristics. The OCC near 5° S is capped by a smooth, corrugated surface, which is covered with serpentinite (found in a dredge), interpreted as a gouge smeared along the corrugated slip surface, facilitating sustained slip on this fault. Below, both seismic data and dredged rocks indicate gabbroic crust. In contrast, the OCC at 22.19° N carries rafted basaltic blocks on top of the detachment fault. Serpentinites have been found on the southern steep flank of the OCC facing to the segment end. The available data suggest that the bulk is made of gabbroic rocks at both OCCs and the crust-mantle boundary is constrained by seismic wide-angle reflections, indicating a profound change of lithology about 4 km below seafloor. We seem to have two styles of OCC formation: In the first case, upper crust (layer 2) is completely transferred to the conjugate ridge flank, while, in the second case basaltic crust remains as rider blocks on the inactive part of the detachment fault, at the footwall. The plate boundary in the shallower part is following the active fault until it is rotated away from its optimum angle and a new fault is created (Mohr-Coulomb criterion). These observations may suggest differences in the thermal regime of the ridge axis. In a cooler setting, the brittle regime may reach down to the mantle, favouring injection of serpentinites into the fault zone and hence weakening the fault. In consequence, a single fault remains active during core complex formation. If heat flow is higher the fault will not reach into the mantle but stay within the lower crust, which hinders deep serpentinisation. A stronger fault may support creation of new faults and rider blocks.

Poster I-28

Serpentinization Along the Mid-Atlantic Ridge (13°-36°N)

Delacour, Adelie; Andreani, Muriel; Godard, Marguerite; Cannat, Mathilde; Picazo, Suzanne Marie; Mevel, Catherine; Ildefonse, Benoit; Dyment, Jerome; Fouquet, Yves

A. Delacour, M. Cannat, S.M. Picazo, C. Mevel, J. Dyment, Geosciences marines, IPGP, Paris, FRANCE; A. Delacour, DTP, OMP-UNIV. PAUL SABATIER, Toulouse, FRANCE; M. Andreani, LST, ENS-Univ. Lyon, Villeurbanne, FRANCE; M. Godard, B. Ildefonse, Geosciences Montpellier, Univ. Montpellier, Montpellier, FRANCE; Y. Fouquet, Ifremer, DRO-GM, Plouzane, FRANCE

Serpentinization consists in the hydration of mantle peridotites, mainly exposed in magma-starved areas along slow-spreading centers. Serpentinites outcropping along the Mid-Atlantic Ridge (MAR) are distinguished, from one site to another, by strong variations in mineral assemblages, chemical and isotopic compositions. In order to characterize the origin of these variations, we conducted a detailed petrologic and geochemical study of serpentinites from four sites located between 13° and 36°N along the MAR (Ashadze, Logatchev, MARK and Rainbow). These four sites were selected because: 1) they are made of variably altered and deformed serpentinites and gabbroic rocks, exposed on the seafloor through a detachment fault, 2) their dome-like morphology has been interpreted as an oceanic core complex, and 3) they host active high-temperature hydrothermal system. Harzburgites and dunites were predominantly recovered at these sites and primary minerals include olivine, orthopyroxene, Cr-spinel and, locally, minor clinopyroxene. Olivine is replaced predominantly by serpentine and magnetite with various textures (e.g., mesh, ribbon). Orthopyroxene is commonly altered to bastite, while relatively unaltered core may be preserved. Serpentine compositions vary between sites (i.e., Fe, Mg, Al, Cl, S) and depend on the primary phases (e.g., Fe enrichment in bastite). Aluminous phases, such as tremolite and/or chlorite, are scarce or absent. In contrast, carbonate veins are abundant and ubiquitous and form, together with serpentine veins, the two predominant vein types. Logatchev and Ashadze serpentinites show four generations of serpentine veins, identical to the V1-V4 vein series identified at MARK (Andreani et al., 2007). Sulfide mineral assemblages are specific to each site suggesting variations in redox conditions, fluid fluxes and fluid chemistry during serpentinization. In spite of their high degrees of serpentinization, most studied samples have compositions close to the mantle fractionation array, Rainbow and Logatchev having the most refractory protolith (avg. $Al2O3/SiO2 < 0.02$). All serpentinites are characterized by enrichment in Pb, Sr and U due to interaction with seawater-derived fluids. Rare Earth Element (REE) patterns show variable enrichments in Light REE (LREE; 0.01 to 0.1 x chondrite) and highly variable Heavy REE contents between sites: Rainbow serpentinites show high LREE concentrations (1 x chondrite) while MARK serpentinites have depleted compositions (0.01 x chondrite), similar to that of the less altered mantle peridotites. Variability in mineralogical and chemical compositions of serpentinites is discussed on the basis of primary compositions of peridotites and vicinity of basalts and/or gabbros, extent of fluid-rock interaction (fluid fluxes and chemistry) and serpentinization conditions (temperature and redox conditions). Andreani et al. (2007) G3, doi:10.1029/2006GC001373.

Poster I-25

Geologic Evolution and Structural Control of the Lost City Hydrothermal Field

Denny, Alden; Kelley, Deborah; Fruh-Green, Gretchen; Ludwig, Kristin; Karson, Jeffrey Alan

A. Denny, D. Kelley, School of Oceanography, University of Washington, Seattle, WA; G. Fruh-Green, Department of Earth Sciences, ETH-Zurich, Zurich, SWITZERLAND; K. Ludwig, Consortium for Ocean Leadership, Washington, DC; J.A. Karson, Department of Earth Sciences, Syracuse University, Syracuse, NY

The southern wall of the Atlantis Massif Oceanic Core Complex is host to the novel serpentinite-hosted Lost City Hydrothermal Field (LCHF). The LCHF is situated near the summit of the Atlantis Massif, ~ 20 km west of the Mid-Atlantic Ridge and ~ 10 km north of the floor of the Atlantis Transform Fault. The core of the field is located on a down-dropped bench, ~70 m below the summit of the massif and is cut by a young, high-angle, north-south trending normal fault. The summit of the massif is marked by a ~ 2 m thick, well-lithified pelagic cap rock that lies unconformably on top of the detachment fault. Direct observations from the human occupied submersible Alvin (2000 and 2003), high definition imagery from the ROV Hercules (2005), and high-resolution (5 m) bathymetry from the AUV ABE (2003) have been compiled into a high-resolution geologic map of the LCHF and adjacent Atlantis Massif. Hydrothermal activity is dominantly focused along the ~60 m-tall, 100 m-long carbonate edifice called Poseidon, which is actively venting 90°C fluid. To the south and west hydrothermal activity rapidly declines, and within 200 m dies off completely. North and east of Poseidon, hydrothermal flow is characterized by egress of diffuse fluids from small, abundant fissures that are predominantly constrained to a 100 m thick, highly deformed mylonite zone. Here, gently dipping, anastomosing networks of fractures channel hydrothermal fluids that issue from near vertical serpentinite walls. Beyond the extent of current hydrothermal activity there is evidence of at least two relict fields, to the south and west respectively, that are not contiguous with the current active field. This strongly suggests that the LCHF has undergone multiple stages of field development progressing to the northeast during its >100,000 years of venting activity. Concurrent uplift, faulting, and intense mass wasting along the southern wall of the massif, along with seismic activity along the Atlantis Transform Fault facilitates migration of venting to the northeast. Carbonate-filled fissures, which cut the cap rock, mark these nascent venting sites.

Poster II-48

Tale of Two Core Complexes: Contrasting Crustal Architecture and Fault Geometries

Dick, Henry

Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA

The Kane Megamullion on the MAR, and the Atlantis Bank Core Complex on the SWIR are two end-members for oceanic core complex formation and crustal accretion. Both expose plutonic basement underlying nearly the length of a magmatic accretionary ridge segment. The discontinuous thin lower crust exposed at Kane contrasts to the >700-km2 1.5-km+ thick Atlantis Bank gabbro massif, clearly showing more robust magmatism at the latter. However, the SWIR spreading rate is 54% of the MAR rate, the offset of the Atlantis II FZ is 46% greater and Na8 of the spatially associated basalts 16% greater – all of which predict thinner crust at Atlantis Bank, and thicker crust at the Kane Megamullion. At the same time, the average composition of Kane and Atlantis II transform peridotites are nearly identical showing that the degree of depletion of the mantle from which the crust was extracted is similar. This is best explained by a more fertile parent mantle beneath the SWIR, and demonstrates that crustal thickness predicted by inverting MORB compositions can be significantly in error.

The Atlantis Bank core complex extends some 37.5 kilometers in the spreading direction, forming a single large dome of turtleback that was later modified by transform parallel faulting. It represents continuous emplacement of gabbroic ocean crust for 3.8 Ma: for at least 2.5 Ma this occurred on a single fault without significant tectonic disruption or cross faulting. Numerous outcrops of intercalated sheeted dikes with gabbro screens are exposed along the length of the complex, demonstrating that gabbros crystallized at depth were continuously rafted upwards into the zone of active diking and then emplaced to the seafloor from beneath a volcanic carapace. These geologic relationships require then, that the detachment fault continuously rooted at the dike-gabbro transition.

By contrast, mapping and seismic refraction at the Kane Megamullion indicate that focused melt flow from the mantle to the crust occurred at different points in space and time beneath the ridge segment giving rise to ephemeral magmatic centers, from which melts were transported along the rift axis to form the volcanic carapace extending over the rift segment. The gabbro bodies appear to represent much smaller intrusions than the Atlantis Bank massif, likely little more than 100 to 200 km2. While intercalated dikes and gabbros are also exposed, so are outcrops of the crust-mantle transition zone. This suggests that the detachment geometry evolved, rooting at the dike-gabbro transition for a time, and then as magmatism waned, plunging downwards to exhume the base of the crust and the shallow mantle. Laterally, along strike, however, even as the detachment rooted at the dike-gabbro transition, massive mantle peridotite was exposed for extended periods of time where the crust appears to have consisted of pillow lavas and sheeted dikes directly overlying mantle peridotite. This raises the possibility that the detachment fault geometry varied along strike, and may account for why the core complex consists of a series of apparently independent domes rather than a single large turtleback reflecting the changing architecture of the crust through time.

Poster I-39

Ridge-transform intersection: inferences from paleomagnetism and structure of the Troodos ophiolite, Cyprus

Ebert, Yael; **Agnon, Amotz**; Abelson, Meir; Ron, Hagai

Yael Ebert, Amotz Agnon, Hagai Ron, The Hebrew University Of Jerusalem, Jerusalem, Israel; Meir Abelson, Geological Survey of Israel, Jerusalem, ISRAEL

Taking advantage of the deeply incised Troodos ophiolite exposes all levels of the oceanic crust (pillow lavas, dikes, gabbro), we reconstruct 3D deformation of the fossil oceanic ridge- transform intersection (RTI),. In order to reconstruct the crustal deformation we have collected paleomagnetic directional data. Twenty-one sites were sampled in both the upper and the lower crust. The data indicate contrasting patterns of deformation between the upper and the lower crust. The sheeted dike complex is twisted about a vertical axis, as expected for an inside corner. Twist saturates at 90°,at a location indistinguishable from the previously inferred RTI corner (MacLeod et al., 1990). The inside corner in the gabbro discerned by paleomagnetic analysis (Granot et al., 2006), is found further off RTI. Between these two domains in the gabbro, the outside-corner tilt and the inside-corner twist, a domain 7 km wide shows the original Troodos mean vector (TMV) (indicating negligible rotation). This domain was interpreted as the fossil neo-volcanic zone (NVZ) in the gabbro layer (Granot et al., 2006). Our paleomagnetic results from the dikes and the gabbro can be reconciled by a 'torsional detachment' as suggested by Granot et al. (2006), where twisted dikes overly the non-rotated gabbro. In addition, we identify a contrasting behavior between the dikes and the gabbro at the very close vicinity of the RTI: where the sheeted dikes have nearly reached their final inside-corner twist, the underlying gabbro shows features of outside corner deformation, i.e. tilting about a horizontal axis. This observation can be explained by an inclined boundary between the transform-controlled inside corner and the divergence-controlled outside-corner. Such an inclined "torsional detachment" can also explain the location offset between the RTI in the dikes level (MacLeod et al., 1990) and the more easterly RTI in the gabbro (Granot et al., 2006).

Poster I-4

Strontium in Primitive Gabbros of Deep Holes 735B and U1309D: Incompatibility with Magmatic Models of Formation of the Third Seismic Layer of Ocean

Efimov, Alexander A.; Puchkov, Victor N.

A.A. Efimov, Institute of Geology an Geochemistry, Ekaterinburg, RUSSIAN FEDERATION; V.N. Puchkov, Institute of Geology, Ufa, RUSSIAN FEDERATION

Primitive olivine gabbros and troctolites, which have no chemical analogues among ocean basalts, constitute the major part of sections of IODP holes 735B and U1309D, drilled on uplifts of the 3rd layer in the Indian and Atlantic oceans [1, 2, 5]. The whole rock abundances of Sr are not discussed by authors of publications [2, 5]. Gabbro represents a kind of a mechanical mixture of femic minerals which practically do not contain Sr, and plagioclase with Sr concentration which is constant for each hole (nearby 300 and 150 ppm respectively). The partition coefficient of Sr between plagioclase crystal and magmatic liquid always exceeds 1. Hence, Sr concentration in late plagioclase and in late liquids should irreversibly decrease upsection. Strict linear dependence between plagioclase amount and whole rock Sr concentration allows to calculate SrPL for any sample in a series. Calculated SrPL in both series is practically constant and does not depend on depth. It is possible to make two important conclusions. The first: there are no signs of decreasing Sr upsection in the studied sections of the 3rd layer predicted by magmatic model of crystallisation of a magma basin. The second: whole rock abundances of Sr in the sections are linear function of amount of plagioclase with constant Sr concentration. This fact is inexplicable in case of the assumption of crystallisation of magmatic liquid in one or several chambers. Each section of the 3rd layer represents a single whole, a product of an only 'creation event'. But there are no reasons to consider it as a product of solidification of a magma chamber (or chambers). Data of marine geophysics speak against a presence of any significant magma chambers in mid-ocean ridges. Incompatibility of these facts with predictions of magmatic models is obvious, and it cannot be ignored. The facts mean equality (uniformity) of chemical potential Sr at the moment of formation of sections. It allows to doubt that sections were formed by crystallisation of a magmatic liquid. Formation of the 3rd layer can be connected with the process of recycling of ancient oceanic lithosphere [4, 6]. Mantle eclogite as a residual product of partial melting of ancient oceanic crust in subduction zones and plumes can be protolith of primitive gabbro [3]. Decompression and sharp inversion of density during an eclogite-to-gabbro retrograde transformation leads to an ascent and merging of gabbro bodies within more dense residual peridotite. Finally the spreading process can lead to formation of the global 3rd seismic layer of ocean. References 1. Blackman D.K. et al.//Proc. IODP. Vol. 304/305. 2006. 2. Dick H.D.B., Natland J.H., Miller D.J. et al.//Proc. ODP, Init. Reports. 1999. Vol. 176./ 3. Efimov A.A., Puchkov V.N. About origin of the ophiolite association. Sverdlovsk, 1980. 63 pp. (In Russian) 4. Hofmann A.W.//Nature. 1997. Vol. 385. P. 219-229. 5. Natland J.H., Dick H.J.B.//J. Volcanol. Geotherm. Res. 2001. Vol. 110. P. 191-233. 6. Sobolev A.V., Hofmann A.W., Nikogosian I.K.//Nature. 2005. Vol. 434. P.

590-597.

Poster I-11

Strain Localization Along Detachment Faults: Mechanical Role of Serpentinite, Talc, Tremolite and Chlorite

Escartin, Javier; Andreani, Muriel; Hirth, Greg

J. Escartin, Geosciences Marines (IPGP), Centre National de la Recherche Scientifique (CNRS), Paris, FRANCE; M. Andreani, Lab. Sciences de la Terre, Univ. Lyon, Lyon, FRANCE; G. Hirth, Dept. Geological Sciences, Brown University, Providence, RI

Oceanic detachments requires efficient strain localization along a fault zone over periods of up to a few Myrs. Geological sampling of the fault zone yields highly deformed fault rocks with a complex interaction with coeval fluid circulation. Lithologies are very variable, with fault schists composed of talc, serpentinite, tremolite and chlorite in different proportions and amounts. Experimental data and characterization of deformation mechanisms exists for serpentinite and talc. Both rocks display low friction coefficients that decrease siginificantly with increasing T (from ~0.2 to <0.1 for talc), and exhibit very efficient strain localization at high T in the brittle or semibrittle deformation regimes. Full crystal plasticity was not achieved under the conditions tested, i.e., the von Mises criterion was never satisfied. The rheology of other phases (chlorite, tremolite), however, is unconstrained experimentally, but their weak nature is supported by the microstructures of natural fault rocks. They often show a close association of chlorite and tremolite with talc and serpentinite, each phase often displaying different modes of deformation (brittle, plastic) operating at the same conditions. Tremolite displays either intragranular fracturing, or ductile deformation by syntectonic growth and later kinking. Talc is either static or syntectonic, with semi-brittle deformation through intragranular sliding and kinking. Chlorite probably reduces fault strength when found with syntectonic tremolite. Serpentine schists are rare, suggesting that deformation is systematically associated with fluid flow and metasomatization along the fault.

Owing both to their weakness and to their unusual mechanical behavior, these fault rocks can control strain localization along detachments, which may accommodate up to 50% of the total plate separation when they operate near-axis. Their weakness can be further enhanced by elevated pore fluid pressure during deformation, as suggested by the geochemistry, deformation microstructures, and the paragenesis of these rocks. The elevated and sustained rates of seismicity associated with detachments, and its extent from 2 to 7 km b.s.f. (TAG detachment), indicates that these materials are not ubiquous or homogeneously distributed, and/or that some of them display velocity weakening; tremolite's characterisitc cataclastic microstrutures may reflect this mode of seismogenic deformation. Talc, which is stable at T<750°C and potentially present to the base of the lithosphere, and serpentinites, stable at T<600°C, have a velocity-strengthening behavior that would promote aseismic slip instead. Small amounts of these alteration products along the fault zone can significantly weaken the detachment, and an heterogeneous and discontinuous distribution may reduce the rupture size of earthquakes, promoting the sustained seismicity rates observed at detachments.

Poster II-68

Hydrothermal Circulation in and Around Detachment Faults: Inferences From Three-dimensional Numerical Modeling

Fontaine, Fabrice J.; Cannat, Mathilde; Escartin, Javier

IPGP-CNRS, Paris, FRANCE

Oceanic low-angle detachment faults expose mantle rocks that are often hydrated by serpentinisation processes, which may play an important role on global element cycles (mass exchanges with the ocean, recycling of water and other components in the mantle and subduction zones). Robust, long-lived high- and low-temperature hydrothermal vent fields have been discovered along segments of slow-spreading ridges (e.g. MAR) in association with detachment faults. To explain vent longevity and the striking correlation with detachment faults, ascending hydrothermal fluids may exploit seismically active detachment faults as flow conduits (McCaig et al., 2007). However, the thermal regime in and around detachment faults is still poorly known and parameters controlling

(i) the generation of high- and low-temperature fields, (ii) their distance to the point of emergence of the fault at the seafloor and (iii) the extent of the hydration processes in the lithosphere are not well constrained. In this work we investigate these issues by means of numerical models of hydrothermal circulation. The models consider convective heat and mass transfers in and around moderate-angle (50°) detachment faults in a three-dimensional geometry. The effect of the permeability structure is specifically and systematically investigated by (i) varying the permeability ratios between the fault zone itself, and the foot- and hanging-walls, (ii) considering the presence or absence of a high-permeability top layer, and (iii) enabling for a more or less sophisticated fault plane geometry as suggested by seismic studies (planar versus convex-upward, 'spoon-like' fault plane, e.g., deMartin et al., 2007). The various simulated three-dimensional flow geometries and thermal regimes are then discussed in the light of the characteristics of the venting styles (e.g., high- versus low-temperature vent fields, distance from the point of emergence of the fault at the seafloor) observed at known peridotites-hosted sites.

Poster I-27

Faults, Fluids and Alteration During the Evolution of an Oceanic Core Complex: Constraints from the Atlantic Massif

Frueh-Green. Gretchen L.; Boschi, Chiara; Delacour, Adélie; Dini, Andrea; Kelley, Deborah

G.L. Frueh-Green, C. Boschi, A. Delacour, ETH Zurich, Zurich, SWITZERLAND; C. Boschi, A. Dini, CNR, Pisa, ITALY; A. Delacour, DTP, OMP-Univ. Paul Sabatier, Toulouse, FRANCE; D. Kelley, School of Oceanography, University of Washington, Seattle, WA

We present a petrologic and geochemical overview that highlights the interplay between deformation, fluid flow and mass transfer during emplacement and alteration of the Atlantis Massif (AM) and the ultimate formation of the Lost City Hydrothermal Field (LCHF). The fact that IODP unexpectedly recovered 1400m of gabbro 5 km north of the peridotite-hosted LCHF is testament to how spatially variable magmatic accretion processes and fluid-rock interaction must be in OCCs. Within the southern wall, gabbroic rocks (~30%) occur as lenses interspersed with pervasively serpentinized spinel harzburgites. The harzburgites have depleted compositions, and most samples show slightly enriched REE contents, interpreted as the result of melt entrapment prior serpentinization. Detachment faulting is marked by talc-amphibole-chlorite metasomatism and heterogeneous distribution of high strain deformation. The metasomatic zones reflect interaction between gabbroic and ultramafic rocks at T <400°C, with localized, channeled circulation of oxidizing, Si-Al-Ca-rich fluids and mass transfer during high strain deformation. Serpentinization in the peridotite-rich domains continued during uplift and was influenced by transform-related normal faulting, volume expansion and mass wasting along the southern wall. High integrated fluid-rock ratios at 150-250°C produced enrichments in B and U, changes in Sr- and Nd-isotope ratios towards seawater values, and highly depleted bulk rock O-, H-, and B-isotope compositions in the basement. In addition, B-isotope analyses of the hydrothermal fluids and precipitates at Lost City indicate that brucite is a significant, temporally variable, reservoir for Mg and B in these systems.

Bulk rock O-, Sr- and Nd-isotope ratios of the gabbroic-dominated central dome indicate variable degrees of seawater interaction at temperatures predominantly under greenschist facies. In contrast to the southern wall, the degree of fluid flow, alteration and mass transfer in the gabbroic domain of the central dome is limited and strongly controlled by veining, igneous contacts, and zones of brittle faulting. Despite differences in sampling approaches, the two areas are distinctly different on a scale of a few kilometers from N to S. Our samples obtained by submersible from the southern wall likely represent the "outer skin" of the system and end-products of long-lived tectonic and hydrothermal activity during formation of the massif as an OCC. Thus, the chemical signatures used to infer sources and fluid fluxes may not be fully representative of the present-day conditions in the basement peridotites that directly feed the LCHF. However, the comprehensive picture given by the geochemical data of the fluids, hydrothermal deposits, and basement rocks at Lost City is that interaction of seawater with both variably fresh peridotites and serpentinized peridotites is crucial to the formation of volatile-rich, Lost City-type systems, and that transform-related normal faulting and mass wasting facilitate seawater penetration necessary to sustain hydrothermal activity over tens of thousands of years.

Oral – Sunday 9th, 11:00

Serpentinization of the Oceanic Lithosphere: Consequences for Hydrothermal Activity and Biogeochemical Cycles

Frueh-Green. Gretchen L.; Boschi, Chiara; Delacour, Adélie; Kelley, Deborah

G.L. Frueh-Green, C. Boschi, A. Delacour, ETH Zurich, Zurich, SWITZERLAND; C. Boschi, CNR, Pisa, ITALY; A. Delacour, DTP, OMP-Univ. Paul Sabatier, Toulouse, FRANCE; D. Kelley, School of Oceanography, University of Washington, Seattle, WA

Exposure of mantle rocks and serpentinization of peridotite are integral components of slow- and ultra-slow spreading ridges. Mantle-dominated lithosphere is a highly reactive chemical and thermal system, in which interaction with seawater during serpentinization has significant geophysical, geochemical and biological consequences for the global marine system. At slow spreading ridges, seawater reacts with peridotite as detachment faults unroof mantle material, and variably serpentinized peridotite hosts black smoker type and cooler off-axis hydrothermal systems. Here we review serpentinization processes as fundamental to understanding the exposure of mantle material and the evolution of oceanic lithosphere formed at slow spreading ridges, and discuss open questions related to heat and fluid flow and the consequences of serpentinization for biogeochemical cycles.

The mineral assemblages and textures of oceanic serpentinites typically record progressive, static hydration reactions that take place under a wide range of temperatures, lithospheric depths, fluid compositions and redox conditions. The products and sequence of serpentinization reactions will be influenced by the flux of seawater penetration into the lithosphere, the bulk protolith compositions, the presence or absence of magmatic intrusions and/or trapped gabbroic melts, and structure (e.g., detachment faults, cataclastic fault zones). In turn, these factors influence vent fluid chemistry, volatile contents, and type of hydrothermal deposits, and distinguish the Lost City hydrothermal field from other known peridotite-hosted hydrothermal systems, such as the Rainbow and Logatchev systems, on the Mid-Atlantic Ridge.

Serpentinization processes have major consequences for long-term, global geochemical fluxes by acting as a sink for H_2O, Cl, B, U, S, and C from seawater and a source of Ca, Ni and possibly Cr to hydrothermal fluids, and by producing extremely reduced fluids. In addition, seafloor weathering of serpentinized abyssal peridotites may result in Mg loss. The formation of H_2 during serpentinization is generally attributed to the production of magnetite during olivine hydration and is described by simplified model reactions with end-member phases. In reality, serpentinization involves solid solutions and metastable reactions governed by local variations in the activities of elements such as Si, Mg, Fe, Ca, and C. Serpentinization of harzburgitic peridotites at temperatures below ~200°C and low fluid-rock ratios produces high alkaline, Ca-rich fluids with elevated concentrations of abiogenic CH_4 and H_2, as exemplified by the Lost City hydrothermal system. The high pH and reducing conditions of such systems dictate that any carbonate species in the fluids are either reduced or precipitated as carbonate before venting on the seafloor, and thus represents an important sink of dissolved (inorganic and organic) carbon from seawater. In contrast to basalt-hosted hydrothermal systems, where conceptual models of the fluid pathways and subsequent reactions and element uptake are relatively well constrained, less is known of the fluid flow and reaction paths or the source and flux of heat in off-axis, serpentinite-hosted hydrothermal systems. The importance of high temperature, peridotite-hosted systems (such as Rainbow) in terms of heat, fluid and chemical fluxes to the oceans at slow and ultraslow spreading ridges has been relatively well studied. However, more detailed studies are necessary to better constrain fluid pathways and the importance of lower temperature diffuse flow and off-axis hydrothermal systems for chemical and thermal exchange between the lithosphere, hydrosphere and biosphere.

Poster I-31

Timing of Exhumation of a MOR-type Gabbroic Intrusion (Internal Ligurian ophiolites, Italy)

Garzetti. Fabio; Tribuzio, Riccardo; Tiepolo, Massimo

F. Garzetti, R. Tribuzio, Dipartimento di Scienze della Terra, Università di Pavia, Pavia, ITALY; R. Tribuzio, M. Tiepolo, Istituto di Geoscienze e Georisorse, CNR, U.O. Pavia, Pavia, ITALY

The ophiolites from Internal Ligurian units of Northern Appennine are lithosphere remnants of a Middle-Upper Jurassic embryonic ocean. These ophiolites are characterised by gabbroic intrusions in mantle peridotites and bear structural and compositional similarities to modern (ultra-)slow spreading ridges. The gabbro-peridotite association shows evidence for exhumation at the seafloor through a polyphase tectono-metamorphic evolution, starting from high temperature ductile conditions. In this work, we wish to measure the exhumation rate of the gabbros, from their intrusion into the mantle to their exposure at the seafloor. This may provide new information on the tectonic processes associated with opening of (ultra-)slow spreading ridges. Geochronological determinations have been thus carried out through single-grain U-Pb zircon datings by laser ablation ICP-MS. On the basis of field relationships relative chronology, we distinguished four main events for the formation and exhumation of the gabbros: (1) formation of gabbroic plutons. The age of gabbro intrusion was determined through zircons separated from plagioclase-rich pegmatoid lenses and from albitite dykelets displaying irregular hornblende-rich contacts against the host gabbro. (2) high temperature deformation in ductile shear zones, which form a low angle with respect to the igneous layering. (3) high temperature brittle deformation associated with melt injections. The ductile shear zones are crosscut at high angles by thin hornblende veins and igneous dykes. The geochemical signature of vein hornblende indicates that the gabbros interacted with seawater-derived fluids. Dykes are basalts with chilled margins and albitites showing sharp planar boundaries to the host gabbros. The age of this event was determined through zircons collected from the second albitite pulse. (4) low temperature brittle deformation leading to the exposure of the gabbros at the seafloor. The U-Pb zircon datings document a long time interval (Ma-scale) between solidification of the gabbros and its uplift to sub-seafloor conditions. This implies a very slow exhumation rate for the gabbro intrusion, in agreement with a "passive" model of mantle uplift and melting.

Poster I-30

Hydrothermal Activity Along the Ultra-Slow Spreading Mid-Cayman Rise

German, Christopher R.; Bowen, Andrew; Coleman, Max; Connelly, Douglas; Honig, David; Huber, Julie; Jakuba, Michael; Kinsey, James; McDermott, Jill; Nakamura, Ko-ichi; Seewald, Jeffrey; Smith, Julie; Van Dover, Cindy; Whitcomb, Louis; Yoerger, Dana

C.R. German, A. Bowen, J. Kinsey, J. McDermott, J. Seewald, D. Yoerger, WHOI, Woods Hole, MA; M. Coleman, Jet Propulsion Laboratory, CalTech, Pasadena, CA; D. Connelly, NOCS, Southampton, UNITED KINGDOM; D. Honig, C. Van Dover, DUML, Beaufort, NC; J. Huber, J. Smith, MBL, Woods Hole, MA; M. Jakuba, University of Sydney, Sydney, New South Wales, AUSTRALIA; K. Nakamura, AIST, Tsukuba, JAPAN; L. Whitcomb, Johns Hopkins University, Baltimore, MD

Thirty years after the first discovery of submarine venting the vast majority of the global Mid Ocean Ridge remains unexplored for hydrothermal activity. Of particular interest are the world's slowest-spreading ridges which were the last to be demonstrated to host high-temperature hydrothermal activity and which may host systems rooted in ultramafic lithologies that are particularly relevant to pre-biotic chemistry and the origins of life. Here, we report the first systematic exploration for and characterization of hydrothermal venting along the short (~110 km), deep (> 5000 m), ultra-slow-spreading (<20 mm yr-1) and geographically isolated Mid-Cayman Rise (MCR). From a combination of CTD casts and tow-yos together with in situ observations from the Nereus hybrid AUV/ROV, we show that the MCR, one of Earth's deepest and slowest-spreading ridges, appears to play host to all three distinct styles of hydrothermal venting known anywhere else in the deep ocean:– (a) neovolcanically-hosted high temperature venting on the rift-valley floor in the northern segment at 4950m - the deepest site yet known in the oceans; (b) tectonically (± ultramafically)-hosted high-temperature venting at the southern end of the MCR and (c) toward the center of the MCR, a low-temperature hydrothermal site located at the summit of a long-lived detachment fault. The latter may represent only the second ever 'Lost City' style vent-site to be found even though it is predicted that they could be widespread. Our work, funded through NASA's ASTEP program, was carried out aboard the RV Cape Hatteras in October-November 2009. As well as being of interest to InterRidge and ChEss (Census of Marine Life) this cruise also represented the first scientific field program funded to use WHOI's new hybrid deep submergence vehicle, Nereus, in both AUV and ROV mode. The discoveries we have already made, together with follow-on investigations planned by the UK in 2010, are poised to render the MCR an ideal natural laboratory for continuing studies of ultra-slow spreading ridges and the wide variety of hydrothermal systems that they host.

Poster I-5

Geochemistry of IODP Site U1309 Gabbroic Series (Atlantis Massif): Evidence for High and Cyclic Magmatic Activity

<u>Godard, Marguerite</u>; Ildefonse, Benoit

CNRS - Universite Montpellier, Montpellier, FRANCE

IODP Site U1309 was drilled at Atlantis Massif, an oceanic core complex, at 30°N on the Mid-Atlantic Ridge (MAR). We present the results of a bulk rock geochemical study (major and trace elements) carried out on 228 samples representative of the different lithologies sampled at this location.

Over 96% of Hole U1309D is made up of gabbroic rocks: olivine-rich troctolites (>70% modal olivine) and troctolites having high Mg# (82-89), high Ni (up to 2300 ppm) and depleted trace element compositions (Yb 0.06-0.8 ppm); olivine gabbros and gabbros (including gabbronorites) with Mg# of 60-86 and low trace element contents (Yb 0.125-2.5 ppm); and oxide gabbros and leucocratic dykes with low Mg# (<50), low Ni (~65 ppm) and high trace element contents (Yb up to 26 ppm). The main geochemical characteristics of Site U1309 gabbroic rocks are consistent with a formation as a cumulate sequence after a common parental MORB melt. (Lack of systematic) downhole variations indicate that the gabbroic series were built by multiple magma injections. In detail, textural and geochemical variations in olivine-rich troctolites and gabbronorites suggest chemical interaction (assimilation?) between the parental melt and the intruded lithosphere.

We carried out mass balance calculations to determine the bulk hole geochemical composition of Site U1309 gabbroic rocks. Bulk hole major element composition is characterized by high Mg# (76) compared to estimates of primitive MORB melt composition (~73). This may reflect under-sampling of the most evolved gabbroic components and/or assimilation of (reaction with) olivine-rich rocks. Calculations carried out to test the effects of sampling biases and of extended assimilation processes result in bulk hole compositions close to that of primary MORB magma for both major and trace elements. This suggests that although troctolites and gabbros form a cumulate series indicating there has been local separation of melt and solids, the most evolved end-members of the Site U1309 gabbroic series are complementary to the cumulate series. These results suggest that (i) there was no large scale removal of melts from this gabbro section and (ii) Site U1309 gabbroic series do not represent the complementary magmatic product of 30°N volcanics.

The occurrence of such a large magmatic sequence implies that high and lasting magmatic activity is associated with the formation of Atlantis Massif. Our results suggest that almost all melts feeding this magmatic system stay trapped into the intruded lithosphere during the OCC formation, but can occasionally reach the surface. Hence, trace element compositions of clinopyroxene and plagioclase poikiloblasts in olivine-rich troctolites indicate that they crystallized from the same depleted MORB melt, which has compositions similar to that of diabases crosscutting the upper part of the borehole and to basalts in the MAR 30 ° N axial region (Drouin et al, 2009). This is consistent with an episodic upper crustal feeding system in the Atlantis Massif area.

Drouin et al. 2009, Chem. Geol., 264: 71-88, doi:10.1016/j.chemgeo.2009.02.013.

Poster I-40

Evidence from the Troodos Ophiolite for Partitioning of Vertical-axis Rotations ('Torsional Detachment') Across the Dike-gabbro Boundary

Granot, Roi; Abelson, Meir; Ron, Hagai; Agnon, Amotz

R. Granot, Institut de Physique du Globe de Paris, Paris, FRANCE; R. Granot, H. Ron, A. Agnon, Institute of Earth Sciences, Hebrew University, Jerusalem, ISRAEL; M. Abelson, Geological Survey of Israel, Jerusalem, ISRAEL

The gabbro suite of the Troodos ophiolite is exposed where an extinct spreading axis (Solea graben) intersects a fossil oceanic transform (Arakapas transform). This is a unique exposure of deep crustal rocks formed at both inside- and outside-corners of a ridge-transform intersection (RTI). Remanence directions from 24 gabbroic sites, positioned along flowline direction, were used as indicators for rigid body rotation of the lower crust. These data complement studies that have reconstructed the brittle deformation of the upper crust and together they facilitate a surprisingly coherent structural model (please see Granot et al., EPSL, 2006, for a complete description). The spatial distribution of lower crustal rotations allow recognition of three regions to which deformation is partitioned: 1) a western region (outside corner) that experienced primarily tilt about horizontal axis 2) a central region with negligible rotation (interpreted as the axial zone) and, 3) an eastern area (inside corner) where vertical axis rotations are dominant. Clockwise-rotated dikes are found at the very close vicinity of the intact central domain, suggesting a 'torsional detachment' between the upper and lower crust at the RTI. Although the nature of the detachment is unclear, our results imply that this motion was accommodated across a narrow zone located at or close to the dike-gabbro transition zone. East of the intact zone, a clockwise rotation in the gabbro increases gradually away from the axial zone, similar to that of the overlying dikes, indicating coupling of the lower crust with the brittle upper oceanic crust at the inside corner. Similarly, coupling is also inferred for the outside corner. The transition from the decoupled layers of sheeted dikes and gabbros in the axial-zone to the dike-gabbro coupling in the inside/outside corners is in keeping with deepening of the brittle-ductile transition away from the hot axial zone.

Poster I-6

Isotopic Insights into Length-scales, Initiation Depths and Extent of High-temperature Hydrothermal Circulation Associated with Oceanic Detachment Fault Systems

Grimes, Craig B.; John, Barbara E.; Cheadle, Michael J.; Valley, John W.; Wooden, Joseph L.

C.B. Grimes, Dept. of Geosciences, Mississippi State University, Mississippi State, MS; B.E. John, M.J. Cheadle, Dept. of Geology and Geophysics, University of Wyoming, Laramie, WY; C.B. Grimes, J.W. Valley, WiscSIMS, Dept. of Geoscience, University of Wisconsin, Madison, WI; J.L. Wooden, USGS-Stanford Ion Microprobe Facility, Stanford, CA

Within the last decade, the application of isotopic dating using zircon recovered from in situ ocean crust has begun providing exciting insights into the complex accretion processes occurring at mid-ocean ridges. Here, Pb/U and (U-Th)/He zircon ages of gabbroic crust exposed in the footwalls of several large-offset, low-angle normal fault systems along the Mid-Atlantic Ridge are combined to investigate footwall cooling histories and apparent length-scales of detachment fault systems. Ti-in-zircon crystallization temperatures, taken with the closure temperature of the (U-Th)/He system in zircon bracket the acquisition temperature of magnetic remanence, defining cooling rates of 1000-2000°C/m.y over the temperature range of ~800-220°C. As these large-offset faults serve as the plate boundary while active, the fault slip rate is taken to be equivalent to the plate-spreading rate at the time of faulting. Assuming the footwall was denuded along a single continuous fault system, and using these slip-rates, the time interval defined by the difference in Pb/U and (U-Th)/He zircon ages can be used to estimate the distance between the ~800 and 220°C isotherms, and therefore the length-scale of the active fault system. At the Atlantis Massif core complex (30° N, MAR) these data suggest a detachment fault length of 10±2 km between the 800 and 200°C isotherms. Lengths of two other fault systems at 15°N, MAR, are calculated to be 9.5±3 km (Hole 1275D) and 5±3 km (Hole 1270D) km. Published Pb/U and (U-Th)/He zircon ages from Atlantis Bank (SWIR) allow calculation of a similar fault length of 7.7±4 km. Using the calculated fault lengths and a fault initiation dip of 50°(consistent with paleomagnetic and bathymetric constraints) we estimate the fault systems along the MAR were active to depths of up to 8 km (~8 km for Atlantis Massif, 8 and 5.5 km at 15°N). A lower initiation dip of 35° (based on magnetic constraints) at Atlantis Bank gives a fault depth of ~6.3 km. These depth estimates for active faulting in slow spreading environments are consistent with microseismicity studies, and the existence of high temperature fault rocks associated with many oceanic detachment faults. The apparent differences in calculated fault initiation depths may reflect variations in the thermal structure beneath the ridge systems, with deeper faults indicating a deeper ~800°C isotherm. Such deep rooting fault systems potentially serve as conduits for high temperature hydrothermal fluid circulation into the deep crust. However, igneous zircon record nearly constant, mantle-like oxygen isotope ratios, and provide no indication of interaction between altered rocks or seawater and the zircon-forming melts. Thus, any significant interaction between seawater and rocks along these faults must have post-dated the formation and crystallization of the latest stage magmas.

Poster II-42

Mylonitic Detachment Faulting Along the Mid-Atlantic Ridge at the Kane Fracture Zone Oceanic Core Complex

Hansen, Lars N.; Cheadle, Michael J.; John, Barbara E.; Dick, Henry J.; Tucholke, Brian E.; Tivey, Maurice A.

L.N. Hansen, University of Minnesota, Minneapolis, MN; M.J. Cheadle, B.E. John, University of Wyoming, Laramie, WY; H.J. Dick, B.E. Tucholke, M.A. Tivey, Woods Hole Oceanographic Institution, Woods Hole, MA

In contrast to oceanic core complexes (OCCs) on the Southwest Indian Ridge and in the Parece Vela basin, some OCCs on the Mid-Atlantic Ridge (e.g., Atlantis Massif) show restricted high-temperature deformation. Thus, low-temperature deformation processes have been considered the controlling processes for Atlantic detachment faults. We challenge this apparent dichotomy between Atlantic OCCs and other OCCs by demonstrating the existence of mylonitic shear zones several hundreds of meters thick at the Kane OCC.

In 2004, the RV Knorr collected samples, bathymetric data, and geophysical data from the Kane Fracture Zone at 23°N on the Mid-Atlantic Ridge. Samples were collected by submersible and by dredging from the complex's surface and from high-angle fault scarps that cut the complex. Examination of the deformed samples by hand sample analysis, petrography, electron backscatter diffraction, and geothermometry confirms that the Kane OCC is bounded by a detachment fault system that initiated at high temperatures (>700°C) and rooted below the brittle-plastic transition. Fault rocks reveal a history of deformation from granulite and amphibolite through subgreenschist facies, including brittle cataclasis. Slopes of the breakaway ridge (>23° to the west and >22° to the east) give constraints on the initial dip of the detachment fault. Assuming this ridge formed by flexural uplift, these slopes suggest the detachment fault formed with a dip >45°.

We present two cross sections through the detachment fault based on samples collected from secondary high-angle normal fault scarps. One section, through Cain Dome, is dominated by peridotite and shows a 450-m thick zone of discrete ductile shear zones overprinted by a 200-m thick zone of semi-brittle and brittle deformation. This mylonitic envelope is on a similar scale to those observed in Hole 735B at Atlantis Bank on the Southwest Indian Ridge [e.g., Dick et al., 2000, *EPSL*] and is consistent with the mylonitic sequence reported by Karson [1999, *Trans. Roy. Soc. Lond.*] at the northern termination of the Kane OCC. An analysis using grain-size piezometry and geothermometry to construct deformation mechanism maps suggests strain rates for the gabbronorites and the peridotites of 10^{-12} s^{-1}, and 10^{-13} s^{-1} respectively. The other section, through Adam Dome, is dominated by gabbroic rocks and exhibits little high-temperature deformation. Although several discrete, high-temperature shear zones are present, this section lies <4 km from the breakaway, and is therefore inferred to have undergone primarily brittle deformation in the shallow crust. Finally, the presence of deformed and undeformed diabase dikes, peridotite mylonites that have been intruded by a gabbroic melt, and Fe-Ti oxide microstructures indicative of deformation with a melt present suggest that detachment faulting was coeval with magmatism. Thus, the Kane OCC provides evidence that detachment faults are consistent with a rolling-hinge detachment fault model and can be influenced by high-temperature processes including mylonitization and interaction with partially molten rocks regardless of location/ridge system.

Poster II-46

Microstructural Development of the Ultramafic Rocks from Godzilla Mullion in the Parece Vela Basin

Harigane, Yumiko; Michibayashi, Katsuyoshi; Ohara, Yasuhiko Y. Harigane, Kanazawa Univ., Kanazawa, JAPAN; K. Michibayashi, Shizuoka Univ., Shizuoka, JAPAN; Y. Ohara, Hydrographic and Oceanographic Depart., Tokyo, JAPAN

Godzilla Mullion, the world's largest oceanic core complex, occurs in the Parece Vela Basin spreading ridge (Parece Vela Rift), the Philippine Sea. Large amount of lithospheric mantle and lower oceanic crustal rocks, including fault rocks from mylonite to cataclasite, has been recovered from the surface of Godzilla Mullion (e.g., Ohara et al., 2009). Harigane et al. (2008) recently analyzed the plastically deformed gabbroic rocks from the breakaway area, and revealed the development of a ductile shear zone in the lower oceanic crust. They argued that the microstructural development of the gabbroic rocks occurred during uplift-related cooling of the gabbro body and that a primary shear zone developed near the breakaway area at depth under anhydrous conditions at high temperatures above 850 degree. In this contribution, we present the microstructural development of the ultramafic rocks from the expanded region of Godzilla Mullion. The ultramafic rocks consist of serpentinized peridotite, serpentinite, serpentinite schist and talc schist. These ultramafic rocks were recovered from nine dredge sites during cruises KR03-1 and KH07-2, and one dive site by the submersible Shinkai 6500 during YK09-05 along a flow line of Godzilla Mullion. In serpentinized peridotites, the serpentine is typically lizardite with minor chrysotile, consisting of mesh texture, bastite and cross-cutted vein in microstructure. The original microstructures of peridotites are preserved as pseudomorph, enabling us to classify them into four types: weakly sheared peridotite, moderately sheared peridotite, mylonite, and ultramylonite. The presence of mylonite and ultramylonite along the surface of Godzilla Mullion suggests an occurrence of shear zone(s) within the deeper part of the oceanic lithosphere. Furthermore, crystallographic-preferred orientation (CPO) data for olivine in mylonite were measured using a SEM-EBSD system at Shizuoka University. Olivine CPO is characterized by a strong alignment of [100] oblique 45 degree to the lineation and [001] in a girdle normal to the foliation, indicating [100](001) pattern. Serpentinite schists and talc schists contain a well-developed schistosity that is overprinted by kinking, whereas one of the talc schists shows mylonitic texture including asymmetric texture and shear band. These serpentinite schists and talc schists are similar to those of the detachment fault-related schists described from OCCs in the Mid-Atlantic and Southwest Indian Ridges (e.g., MacLeod et al., 2002; Escartín et al., 2003). The presence of such schists along the surface of Godzilla Mullion indicates that they were derived from shear zone(s) in the cold (i.e., shallow) oceanic lithosphere at greenschist facies condition. Such developed shear zone(s) in both deeper and shallower oceanic lithosphere could play an important role on the structural evolution of the Godzilla Mullion in the Parece Vela Rift. We interpret that these ultramafic rocks were formed in the shear zone(s) in both deeper and shallower oceanic lithosphere, presumably associated with detachment faulting throughout the Godzilla Mullion during tectonic extension within the Parece Vela Rift.

Poster II-43

Pervasive Reactive Melt Migration Before Core Complex Formation: Evidence From IODP Hole U1309D, Atlantis Massif

Hellebrand, Eric; Suhr, Guenter; Johnson, Kevin; Brunelli, Daniele; von der Handt, Anette

E. Hellebrand, K. Johnson, A. von der Handt, Geology & Geophysics, University of Hawaii, Honolulu, HI; G. Suhr, Geology & Mineralogy Inst., University of Cologne, Cologne, GERMANY; D. Brunelli, DST, University of Modena, Modena, ITALY; A. von der Handt, Geoscience Institute, University of Freiburg, Freiburg, GERMANY

Drilling at Hole U1309D (IODP Legs 304/305) penetrated 1415 m into the footwall of the Atlantis Core Complex. More than 96% of all recovered rocks are gabbroic and only minor peridotite slivers were found. The complexly stacked gabbroic sequence ranges from primitive olivine-rich troctolites to (olivine) gabbros and gabbronorites to highly evolved oxide gabbros and leucocratic dikes.

Most lithologies preserve evidence for pervasive, and partly multistage, reactive melt transport. The most clearly visible overprint occurred after formation of cumulus grains and is manifested by a Ti enrichment at cpx grain boundaries. Prior to that, a more focused reactive melt transport occurred, leading to cpx formation at the expense of a compacted olivine-plagioclase framework. These reactions occur throughout the entire core.

Since their recovery, the origin of the olivine-rich troctolites (ORT) has been intensely debated, and a possible mantle origin was discussed on board (Blackman et al 2006). According to textural criteria, the ORT resemble primitive cumulates, albeit fine grained. In contrast to these textural constraints, geochemical and microstructural criteria suggest that may represent reacted and impregnated mantle peridotites (Blackman et al 2006; Suhr et al 2008; Drouin et al 2009; Drouin et al, in press). Suhr et al (2008) argue that the ORT are former mantle rocks which were converted to dunite at the base of the upper magmatic unit. Later, as melts derived from the lower magmatic unit percolated, they were gradually equilibrated to a more evolved chemistry and transformed to a fine grained ORT. The main arguments against a cumulate nature of the ORT are the lack of any systematic down-hole trend in compatible elements within the ORT, its distinctly fine-grained microstructure, the high Cr-content of cpx, and its Ni-rich olivine composition. The high NiO for a given Mg/(Mg+Fe) in the ORT can be modeled by simple equilibration of relict mantle olivine with a somewhat evolved melt. Independent from the compatible element behavior, strongly depleted trace element abundances in olivine have also been proposed to support a mantle origin of these rocks (Drouin et al., 2009).

However, these criteria are not sufficiently conclusive and appear to be inconsistent with the extreme heterogeneity observed within the ORT-hosted Cr-spinels. Not only do the spinels resemble compositions observed in primitive MORB, they are entirely unlike any peridotitic spinel found on the ocean floor or in the mantle section of ophiolites. The exact origin will continue to be subject of further study.

However, independent of whether the ORT directly crystallized from a melt or whether they formed from by reaction with a mantle protolith, proportionally large amounts of melt are required to form these rocks. Considering that the occurrence of sparse truly mantle harzburgites at this location requires an earlier period of low magma supply and presumably thin magmatic crust, this pulse of high melt supply must predate or at best coincide with the onset of core complex formation.

Poster I-20

Comprehensive Shallow Coverage of Seismic Velocity Structure at Atlantis Massif Oceanic Core Complex

<u>Henig, Ashlee S.</u>; Blackman, Donna K; Harding, Alistair J; Kent, Graham M; Canales, Juan Pablo

A.S. Henig, D.K. Blackman, A.J. Harding, Scripps Institution of Oceanography, La Jolla, CA; G.M. Kent, Nevada Seismological Lab, University of Nevada, Reno, Reno, NV; J. Canales, Woods Hole Oceanographic Institution, Woods Hole, MA

Using multichannel seismic (MCS) data, we finalize our investigation of the detailed velocity structure of the uppermost ~km of Atlantis Massif, an oceanic core complex (OCC) at 30°N on the Mid Atlantic Ridge. Our analysis includes all MCS lines sampling the massif. We employ the Synthetic On-Bottom Experiment (SOBE– Harding et al., 2007; Arnulf et al., 2009) processing method to downward continue all lines to the seafloor, producing models with unprecedented structural detail in the upper few hundred meters subsurface. Our velocity inversions for axis-parallel lines covering the domal core show velocities within a few hundred meters of the seafloor ranging 5.5-6.5 km/s. Based on the continuity of this structure we interpret the signature to indicate a large gabbroic body. This petrologic inference is consistent with deep drilling that retrieved a 1.4 km nearly-continuous gabbroic section from the central dome of Atlantis Massif (Blackman et al., 2006). The continuity of this velocity feature does not support the idea of a discreet fault or lithological contact between the two main structural components of the massif- the central dome and the southern ridge. Also apparent from our velocity models is a structural unit of few hundred meter thickness with comparatively lower seismic velocities, more akin to normal young Atlantic shallow crustal structure, capping the western, northern, and southernmost portions of the OCC. The spreading-parallel MCS lines show significant lateral variation in velocity structure between the earliest-exhumed side of the massif, where velocities are lower (2.5-3.5 km/s in the upper few hundred meters), and the most recently exhumed side, where velocities are comparatively higher in the few hundred meters immediately subseafloor (4.5-6 km/s). This lateral variation can be attributed to an increase in permeability and alteration of the subsurface with an increase in age of exposure, or could be a result of different lithologies within the massif. Recently completed analysis of the MCS line traversing the hanging wall to the detachment reinforces prior interpretations of a volcanic composition for the overlying block on the eastern edge of the massif. Thus, our velocity models suggest significant lateral heterogeneity within the upper (~1 km) structure of the Atlantis Massif. Likewise, we observe large vertical velocity gradients >4 s⁻¹, in the upper few hundred meters of structure, but never observe fresh mantle velocities >7.5 km/s within the coverage area of the MCS refraction, down to ~1 km depth.

Poster I-37

Similarities in Structure of Uppermost Oceanic Crust of the Hess Deep Rift and Pito Deep with the Sheeted Dike Complex of the Troodos Ophiolite

Hurst, Stephen D.

Geology, Univ. of Illinois, Urbana, IL

Direct observations of the uppermost 2 km of the oceanic crust exposed at the Hess Deep Rift and Pito Deep reveal substantial similarities with structure of the sheeted dike, extrusive section and uppermost gabbros of the Troodos Ophiolite. At the largest scale, all locations show dramatic variations in the thickness of both basaltic volcanic and sheeted dike rock units. In addition, all have extensive (>= 10km width) exposure of moderately dipping (40-70°) sheeted dike units. In Troodos, the west side of the Solea Graben is the most extensive and best exposure of the tilted dikes and is underlain by a horizontal detachment fault separating the gabbro from the dikes. Paleomagnetic evidence and slickenside analysis of small faults in the uppermost gabbro and lowermost sheeted dikes indicate that the dikes rotated 40-90° consistent with extension on this and parallel faults, accounting for up to 40 xtension. No such detachment has yet been definitely observed at either Hess Deep or Pito Deep. At Hess Deep in particular, lowermost dikes and uppermost gabbros appear as a gradational contact with interfingering of diabase and gabbro. However, similar gradations and interfingering is exposed in Troodos just to the east of the Solea Graben, northwest of Spilia. Other interesting similarities include the several km wide area of massive diabase observed at Pito Deep and several areas of Troodos, including north of Spilia and south of Lemithou. Overall, these structural patterns at Hess Deep and Pito Deep have been interpreted in terms of fluctuations in the relative contributions of dike intrusion and subsidence/volcanic construction during crustal accretion. Large parts of the Troodos Ophiolite must have accreted in a manner and environment similar to the fast-spread crust at Hess Deep and Pito Deep and thus may have been created in a fast spreading environment.

Poster I-12

The Atlantis Massif : An Illustration of the Interplay Between Core Complex Development and Magmatic Activity

Ildefonse, Benoit; Godard, Marguerite; Drouin, Marion

B. Ildefonse, M. Godard, Géosciences Montpellier, CNRS - Université Montpellier 2, Montpellier, FRANCE; M. Drouin, Laboratoire Géosciences Réunion- IPGP, Université de la Réunion, Saint-Denis, REUNION

Oceanic Core complexes expose intrusive crustal rocks via detachment faulting, and are generally associated with serpentinized mantle peridotite on the seafloor. All of the

ODP/IODP drilling at 4 different OCC, including Hole U1309D, have recovered only gabbroic sections, with almost no serpentinized peridotite. Ildefonse et al. (2007, doi:10.1130/G23531A.1) have proposed a possible revised model for OCC development in which the "core" of the OCC domes represents a period of greater than typical mafic intrusion in overall magma-poor regions of slow/ultra-slow spreading ridges. Exposure of the gabbroic intrusion(s) is enabled by deformation that localizes predominantly within the serpentinized peridotite that surrounds them. The proposed model was different from previous published models in that OCC represent the tectonic and morphologic expression of the magma-rich end-member of a fundamental mode of crustal accretion- the intrusion of gabbro plutons at depth, in an heterogeneous "plum pudding" type of crust; it is consistent with recent seafloor observations and numerical modeling suggesting that OCC do not represent the magma starved end-member of mid-ocean ridges.

An illustration of the vigorous magmatic activity associated with OCC is the occurrence of olivine-rich troctolites in Hole U1309D. We present a petrostructural (EBSD) and in-situ geochemical (EPMA, LA-ICPMS and LA-HR-ICPMS) study of olivine-rich troctolites (ol > 70%; 5.5 % of recovered section) and associated gabbros (Drouin et al., 2009, doi:10.1016/j.chemgeo.2009.02.013; submitted). Trace element compositions of clinopyroxene and plagioclase poikiloblasts in olivine-rich troctolites indicate that they crystallized from the same depleted MORB melt. Olivine trace element compositions appear too depleted in light REE to be in equilibrium with plagioclase and clinopyroxene. Olivine crystallographic preferred orientations are weak, and misorientations are consistent with deformation by dislocation creep with activation of the high-temperature (010) [100] slip system, commonly described in asthenospheric mantle. The fabrics also display a relatively strong uncommon [001] concentration that we interpret as resulting from abundant melt impregnation. The joint study of geochemical processes and microstructures in olivine-rich troctolites suggest a complex crystallization history in an open system with percolation of large volume of MORB-type melt that postdate olivine crystal-plastic deformation. This is consistent with the formation of OCC associated with relatively strong magmatic activity, and with the crystallization of most of melt in the Atlantis Massif lithosphere without basaltic counterpart erupted on the seafloor. Although the mantle origin of the olivine is difficult to demonstrate unequivocally, we propose that olivine-rich troctolites represent the ultimate residue of melt-mantle reaction processes.

Poster I-2

Melt-rock Interaction and Its Impact on Serpentinization of Abyssal Peridotites

<u>Joens, Niels</u>; Bach, Wolfgang; Klein, Frieder; Schroeder, Timothy

N. Joens, W. Bach, F. Klein, University of Bremen, Bremen, GERMANY; F. Klein, Woods Hole Oceanographic Institution, Woods Hole, MA; T. Schroeder, Bennington College, Bennington, VT

Interaction of peridotites and seawater leads to serpentinization, which affects the physical and chemical characteristics of oceanic lithosphere. We examined abyssal serpentinites exposed in the footwalls of major detachment faults on the flanks of the slow-spreading Mid-Atlantic Ridge near the 15°20′N fracture zone (Ocean Drilling Program Leg 209, Site 1270). The study is aimed at understanding the relations between magmatism, hydration reactions, shear zone formation and fluid flow.

The examined serpentinites are hydrated harzburgites with an alteration degree of >90%. Olivine is replaced by serpentine minerals and magnetite in a typical mesh texture, whereas bastite after orthopyroxene is almost magnetite free. Brucite has not been identified. We have specifically picked out samples that are crosscut by narrow (<15mm) shear zones. Within these shear zones rocks are of strongly foliated appearance and consist of magnesium-rich chlorite and tremolitic/actinolitic amphibole. In addition, these "fault schists" contain porphyroclasts of brownish magnesiohornblende as well as accessory apatite and zircon. Whole-rock geochemical and oxygen isotope analyses have been perfomed on separated fault schists and associated serpentinite host rocks. In accordance with results from mineral chemistry, Ti-in-zircon thermometry and reaction path modeling, fault schists are interpreted to represent hydrated former plagiogranitic melt veins. The presence of evolved melts within abyssal peridotites has important consequences on both the chemical and the structural evolution of detachment fault systems. The fundamentally different hydration behaviour of plagiogranites and peridotites leads to an early high-T (≈500°C) hydration of plagiogranitic melt veins and subsequent focussing of shear zones on the hydrated rock portions. At these temperatures the surrounding peridotite is still stable under hydrous conditions. Whole-rock oxygen isotope analyses of fault schists indicate that the high temperature shear zones are zones of increased fluid flow and thus represent the starting point for effective serpentinization upon further cooling to temperatures below ca. 350°C.

Increased fluid flow along melt-impregnated shear zones might suggest that the composition of nearby issuing hydrothermal vent fluids is strongly influenced by phase relations in hydrated melt veins. However, due to their overall small volume and high fluid-rock mass ratios, their influence on vent fluid compositions of hydrothermal vent systems is supposedly insignificant. In contrast, they have a comparatively large impact on chemical composition and phase relations of adjacent ultramafic host: the high chemical potential gradient between shear zone-hosted fluids and serpentinite host rocks impresses a metasomatic zoning. An important effect is prevention of brucite formation due to increased silica activity. Apart from that, rare earth elements are strongly enriched at the vein interface. In combination, our multidisciplinary study suggests that evolved melts intruding into mantle rocks exert a hitherto underestimated influence on fluid-rock interactions within detachment faults.

Oral – Tuesday 11th, 14:00

Oceanic and Continental Detachment Fault Systems: How Similar Are They?

John, Barbara E.; Cheadle, Michael J.

Dept of Geology and Geophysics, Laramie, WY

Detachment faults and their associated core complexes occur both in continental rifts and at mid-oceanic ridges, and represent a fundamental mode of crustal extension. Both continental and oceanic detachment faults are characterized by corrugated, domal topography; exposures of the fault surface extend tens of kilometers in the slip direction, with dips ≤20°. In each system, the faults comprise a network of anastomosing fault zones, locally comprising mylonite, overprinted by a damage zone of cataclasite, breccia and gouge one – to a few hundred meters thick, exhibiting a progressive down-temperature continuum in deformation. Both form at strain rates ~10^{-12}–10^{-14}/sec and accommodate asymmetric extension.

Despite these similarities, the two systems exhibit significant differences, controlled by their environments of formation. Oceanic core complexes form in thinner lithosphere, with higher geothermal gradients, dominated by olivine and feldspar rheology. In contrast, deformation associated with continental detachment faults is controlled by quartz and feldspar rheology. Oceanic detachment faults also have a more intimate association with magmatic accretion. Hydrothermal circulation and consequent alteration are more pronounced in oceanic detachment systems, dominating the low-temperature fault evolution, and likely seismicity. Oceanic detachment faults are rolling-hinge type normal faults. In contrast, some continental detachment systems were clearly initiated at low angle (dips <20°). Detachment faults cutting oceanic lithosphere are non-conservative; footwalls are much more extensive than the hanging wall of the fault. Beneath continental core complexes lower crustal flow maintains crustal thickness despite significant extension. Lower crustal flow beneath oceanic core complexes is limited and restricted to the environs of the magma chamber.

One final contrast between the detachment systems is that mylonitic rocks, and hence crystal-plastic shear zones, are relatively common in continental and rare in oceanic core complexes. Following Hirth et al (1998), we argue that this is a simple consequence of crustal rheology. In continental core complexes the onset of plasticity of quartz is ~300°C. The temperature window for mylonite formation therefore extends many hundreds of degrees, and several million years at cooling rates of ~100°C/m.y. In contrast, oceanic core complexes, which host gabbroic footwalls, have a narrow temperature window for plastic deformation.

Typically this window is defined by the solidus of evolved melts (850°C for oxide bearing gabbros), and the brittle plastic transition of 'dry' plagioclase (750°C). Consequently the timescales for formation of mylonitic shear zone formation are short, due to the high cooling rates (2000°C/m.y.) associated with core complex denudation.

Poster I-13

Detachment Shear Zone Exposed on the S. Wall of the Atlantis Massif Core Complex, Mid-Atlantic Ridge 30°N

Karson, Jeffrey A.; Kelley, Deborah; Frueh-Green, Gretchen L.

J.A. Karson, Department of Earth Sciences, Syracuse University, Syracuse, NY; D. Kelley, School of Oceanography, University of Washington, Seattle, WA; G.L. Frueh-Green, Department of Earth Sciences, ETH-Zürich, Seattle, SWITZERLAND

High-resolution bathymetry and near-bottom observations document the subhorizontal detachment shear zone at the top of the Atlantis Massif Oceanic Core Complex near the intersection of the Mid-Atlantic Ridge and the Atlantis Transform Fault. Faulting and mass wasting along the transform valley wall expose a cross section of the lower plate of the core complex that contrasts with results from IODP deep crustal drilling on the crest of the massif about 5 km to the North. The shear zone is inferred to be responsible for the unroofing of lower crustal gabbros and upper mantle peridotites by extreme, localized tectonic extension during seafloor spreading over the past 1.5-2 Ma. The shear zone is about 100 m thick and can be traced for at least 3 km in the tectonic transport direction. Within this zone, cm-dm thick domains of mylonitic serpentinized peridotites and metasomatic talc- and/or amphibole-chlorite-rich rocks occur together with less deformed peridotites and metagabbros and reflect strain localization and focused fluid flow. Fresh high-T peridotite mylonites locally preserve unaltered olivine relicts, suggesting an early, high-T history of the fault zone. The detachment shear zone is cut by numerous steeply dipping normal faults and shear zones that predate the development of an aerially extensive sheet of sedimentary breccias and carbonates that cap the massif. The late faults localize serpentinization-driven hydrothermal outflow at the Lost City Vent Field located at the crest of the massif. Structural features reveal a history of intense noncoaxial shear with strain localization and focused fluid flow followed by coaxial flattening of the massif with serpentinization and volumetric expansion. Debris slide breccias and pelagic limestones are interpreted in terms of the progressive rotation of the shear zone from moderately inclined toward the median valley axis to its present, broadly arched, subhorizontal form. Active faulting and mass wasting help maintain ongoing serpentinization and resulting hydrothermal venting.

Poster I-38

Fault-related Oceanic Serpentinization in the Troodos Ophiolite, Cyprus: Implications for a Fossil Oceanic Core Complex

Katzir, Yaron; Nuriel, Perach; Abelson, Meir; Valley, John W; Matthews, Alan; Spicuzza, Michael J; Ayalon, Avner

Y. Katzir, P. Nuriel, Geological and Environmental Sciences, Ben Gurion University of the Negev, Be'er Sheva, ISRAEL; M. Abelson, A. Ayalon, Geological Survey of Israel, Jerusalem, ISRAEL; J.W. Valley, M.J. Spicuzza, Geoscience, University of Wisconsin, Madison, WI; A. Matthews, Earh Sciences, The Hebrew University of Jerusalem, Jerusalem, ISRAEL

Heavily serpentinized ultramafic rocks occur adjacent to a major axis-parallel fault, the Amiandos Fault (AF), at a fossil ridge-transform intersection (RTI) in the Troodos ophiolite (Fig. 1). So far, serpentinization and faulting were not considered to be related to the Cretaceous ocean spreading history of the Troodos ophiolite, but instead were interpreted as associated with late, emplacement-related tectonics and diapirism. Here, petrographic and stable isotope tracers (δD, $\delta^{18}O$) of water-rock interaction are examined in three profiles across the AF to determine the spatial distribution, temperature, and the type of water involved in serpentinization in the Troodos RTI. Two distinct serpentinization events were identified: 1) Low-$\delta^{18}O$ serpentine (4.6 to 6.6‰) that occurs close to the AF probably formed by fault-localized hydrothermal (100-200°C) alteration initiated by deep infiltration of seawater during seafloor spreading. 2) This was overprinted by pervasive high-$\delta^{18}O$ (10.6-12.6‰), low-δD (–70 to –86‰) low-temperature hydration and chrysotile veining that may have occurred during ophiolite emplacement. Post-magmatic decrease of $\delta^{18}O$(plagioclase) in non-amphibolitized gabbros in the footwall of the AF suggests high-temperature, off-axis gabbro-water interaction and focused fluid flow extending to the lower crust through the AF zone. The Amiandos Fault was thus active during seafloor spreading, operating as a detachment fault in a core complex structure, and progressively exhuming deeper levels of the oceanic lithosphere. This scenario is supported by additional observations such as proximity to RTI and spatial association with highly-rotated blocks in the sheeted dikes.

Oral – Friday 14th, 14:00

Evaluating In Situ Mineral Carbonation in Near-Seafloor Peridotite for CO_2 Capture and Storage

Kelemen, Peter; Matter, Jürg; Streit, Lisa; Paukert, Amelia

Lamont Doherty Earth Observatory, Columbia University, Palisades NY 10964

Recent studies have shown that reaction of tectonically exposed peridotite with the atmosphere, ground water, and seawater, is actively forming solid carbonates, both in ophiolites and on the seafloor. Despite the fact that this process increases the solid volume, geochronological data show that porosity, permeability and reactive surface area are maintained, or even increased, during reaction over tens to hundreds of thousands of years. We've proposed that this occurs because the volume increase due to olivine carbonation is large enough to create large stresses that, in turn, fracture the rock.

Kinetic studies of olivine carbonation show that the rate is maximized near 185°C over a range of CO_2 partial pressures from surface conditions to hundreds of bars. When the reaction is catalyzed by fluids with high $NaHCO_3$ concentration at 185°C and > 70 bars PCO_2, the rate is millions of times faster than the natural process at surface conditions.

The combination of natural rates and kinetic data suggests the possibility of enhancing natural peridotite carbonation reactions in order to create a significant sink for anthropogenic CO_2 emissions to the atmosphere. An engineered technique would be to create access for CO_2-rich fluids, or seawater, to circulate through peridotite at about 185°C. We have considered two methods: (1) use of nearly-pure CO_2 captured from fossil fuel extraction and from power plants, or (2) use of surface seawater, with return of CO_2 depleted water to the surface. The first is hundreds or thousands of times more efficient, in terms of kg CO_2 converted to solid carbonate per kg peridotite per second, and provides substantial exothermic heat production that can maintain a rock volume at the optimal temperature for reaction. However, the second could be much less expensive, because it avoids the costs of industrial CO_2 capture and transport, and provides a method for geologic CO_2 capture as well as storage. Both methods would benefit from, and the second method requires, access to a large volume of peridotite that is already close to the optimal temperature for olivine carbonation.

Tens of percent of the seafloor at slow spreading ridges is thought to be underlain by tectonically exposed peridotite in oceanic core complexes. Many near-ridge, near-seafloor peridotites remain at high temperature due to the presence of gabbroic intrusions. Together with many other workers, we propose accelerated study of near seafloor peridotites in this context. What are natural rates of peridotite carbonation on and near the seafloor, beneath established hydrothermal vents and in lower temperature settings? What is the subsurface evolution of carbonate veins, fractures, permeability, reactive surface area, and fluid flow in peridotites? How might peridotite carbonation be enhanced? What would be the least expensive and most effective way to transport surface waters to seafloor peridotites? What can be learned from natural hydrothermal convection, about inducing and maintaining fluid flow without substantial pumping?

While the proposed research outlined here is catalyzed by the potential for CO_2 capture and storage, it is also inspired by fundamental science questions of great importance, ranging from the physical processes of fluid transport to global geochemical cycles. For example, what are the regimes in which increasing solid volume causes reaction-driven cracking, versus the regimes in which porosity, permeability and reactive surface area decrease, greatly limiting reaction progress? What is the global flux of subducting carbon in near-seafloor peridotites, and what is its fate? Also, there are many synergies between research on peridotite carbonation and related fields of current interest, including the processes of serpentinization, the potential role for serpentinization in the origin of life on this and other planets and in the present-day biosphere, the tectonic processes that form oceanic core complexes, the nature of oceanic crust at slow spreading ridges, and the origin and fate of gabbroic intrusions emplaced into peridotite.

Oral – Tuesday 11th, 09:45

Linkages Among Serpentinization and Life in Ultramafic-hosted Hydrothermal Systems: The Lost City Hydrothermal Field

Kelley, Deborah S.; Brazeton, William J.; Proskurowski, Giora; Früh-Green, Gretchen L.; Baross, John A.; Lilley, Marvin D.; Ludwig, Kristin A.; Lang, Susan Q.

D. S. Kelley, W. J. Brazeton, J. A. Baross, M. D. Lilley, School of Oceanography, Univ. of Washington, Seattle, USA; G. Proskurowski, Woods Hole Oceanographic Institution, Woods Hole MA, USA; G. L. Früh-Green, Susan Q. Lang, ETH Dept. Earth Sciences, Zurich, SWITZERLAND; Kristin A. Ludwig ,Department of Public Affairs, Consortium for Ocean Leadership, Washington D.C.

For over two decades, high-temperature, acidic black smoker systems were believed to be the norm along the Mid-Atlantic Ridge (MAR). However in 2000, the discovery of the Lost City Hydrothermal Field hosted not in the axial valley, but instead ~15 km west of the MAR, fundamentally changed our views about submarine hydrothermal systems and where and how life can exist in the oceans. Extreme attenuation of the crust and formation of long-lived detachment faults may be key to formation of present-day Lost City-type systems.

Lost City is characterized by extreme conditions never before seen in the marine environment: venting of pH 9-11, >90°C, metal-poor fluids from carbonate edifices that tower 60-m above the seafloor. The young, aragonite- and brucite-dominated chimneys are devoid of metals and are characterized by highly sinuous flow channels with porosity >50%. The high-pH fluids are dominated by bicarbonate and carbonate species. When these fluids mix with seawater, carbonate ions combine with Ca^{2+} from the vent fluid to form $CaCO_3$. In contrast to nascent chimneys, old deposits are dominated by calcite and have porosity values < 5%. Progressive bathing of the inactive structures in seawater results in incorporation of Co, Cr, V, Ni, Sr and U into the structures. U/Th dating of active and extinct carbonate structures shows that hydrothermal activity has operated for >120,000 years. Long-lived flow is likely facilitated by seismic activity associated with the Atlantis Transform Fault, volume expansion and fluid over-pressuring within the serpentinite basement rocks, and an abundant supply of fresh mantle material within the south face of the Atlantis Massif.

Moderate to low-temperature (<150-200°C) fluid-rock reactions in the underlying ultramafic rocks result in alkaline fluids with high concentrations of abiogenically produced H_2 (up to 15 mmol/kg), CH_4 (1-2 mmol/kg), and other low molecular weight hydrocarbons that support novel microbial communities. The Lost City fluids contain higher concentrations of formate and acetate than any other non-sedimented hydrothermal system studied to date. While formate is likely abiogenic, acetate concentrations strongly correlate with H_2 across the field, indicating that it likely results from microbial activity. The anoxic, warm (>80°C) interior zones of the chimneys harbor biofilms containing 10^6-10^9 cells g/$CaCO_3$: >80% of these cells belong to a single phylotype of archaea called Lost City *Methanosarcinales (LCMS)*. Surprisingly, simultaneous methanogenesis and anaerobic CH_4-oxidation may be occurring in the LCMS biofilms. Inactive carbonate deposits, or chimneys that are only weekly venting, contain anaerobic methanotrophic organisms (ANME-1), providing strong support that ecological succession has occurred within the chimneys. In contrast to the carbonate-hosted communities, *Thermococcus species* affiliated with black smoker systems were recovered from Lost City vent fluids, perhaps reflecting the presence of a hot, subseafloor biosphere beneath the field. Bacteria, phylogenetically related to CH_4- and S-oxidizers, are mostly found in the oxygenated, outer walls of chimneys where fluid chemistry is substantially different than the chimney interiors. Results from pyrosequencing show that the archaeal and bacterial biofilm communities underwent dramatic changes as environmental conditions in the chimneys changed over a 1,200-year period.

Considering the global distribution of ultramafic environments and the potential importance of these systems to the origin of life and to models of Earths' earliest microbial ecosystems, study of Lost City has the potential to yield new discoveries with implications for understanding the linkages between abiotic water-rock reactions and microbial evolution.

Poster II-45

CO2-metasomatism and the Formation of Talc in Oceanic Detachment Faults

Klein, Frieder

Woods Hole Oceanographic Inst., Woods Hole, MA

Dynamic recrystallization of serpentinite to talc schist is a prominent feature of oceanic detachment faults and crucial for localizing shear stress; however, conditions and processes during talc formation remain poorly constrained. To transform magnesian serpentine (Mg/Si=1.5) to talc (Mg/Si=0.75) massive removal of Mg or addition of Si is required. As the solubility of Mg is very low in fluids with pH>3, metasomatic enrichment of silica transported away from gabbroic intrusions appears to be a plausible explanation. Based on petrographic observations and phase petrological examinations an additional, equally plausible process to form talc in oceanic detachment faults is explored. Talc-magnesite veins and schists crosscutting serpentinite on land are commonly attributed to the ingress of CO2-rich fluids, either related to magmatic degassing or decarbonation of sediments. The simplified succession of mineral assemblages during progressive carbonation of serpentinite is as follows: (1) serpentine brucite, (2) serpentine magnesite, (3) magnesite talc, and finally (4) magnesite quartz (e.g., Hansen et al., 2005). Talc-magnesite altered serpentinite, recently described in rocks from the Atlantis Massif (IODP Leg 304 Hole 1309B, Shipboard Scientific Party, 2006), suggests that CO2-metasomatism is taking place in oceanic serpentinites as well. Here, thermodynamic calculations are used to explore carbonation of oceanic serpentinite in relation to fluid composition and temperature. Vent fluids emanating from high-T hybrid ultramafic/mafic-hosted hydrothermal systems (e.g., Logatchev, Rainbow) are strongly enriched in CO2 (10 – 16 mmol/kg) compared with seawater (Charlou et al., 2002), though at T ≥ 350°C phase relations indicate that CO2 concentrations will not suffice to drive carbonation. Magmatic degassing during crystallization of a gabbroic intrusion may foster carbonation even at very high temperatures, as CO2 concentrations are expected to increase dramatically (cf. Seewald et al., 2003). In vicinity of Hole 1309B, the Lost City hydrothermal field emanates low-T, CO2-poor (< 26 µmol/kg) fluids (Proskurowski et al., 2008). As minimum CO2 concentrations necessary for mineral carbonation decrease markedly with decreasing T, at T≤100°C CO2 concentrations in a µmolal range would be sufficient to destabilize brucite in favor of magnesite. However, low CO2/3He ratios at Lost City indicate that mantle CO2 has been removed before venting; assuming the predicted, much higher CO2 concentrations of up to 4.1 mmol/kg (Proskurowski et al., 2008), phase relations indicate a thermodynamic drive for talc-magnesite formation at T≤ 175°C. In combination, there may be a synergistic effect of Si- and CO2-metasomatism on weakening oceanic detachment faults from high to low T.

Charlou, J.-L., et al., 2002. Chemical Geology, 191: 345-359. Hansen, L.D., et al., 2005. Canadian Mineralogist, 43: 225-239. Proskurowski, G. et al., 2008. Science, 319: 604-607. Seewald, J.S., et al., P.J., 2003. Earth Planet. Sci. Lett., 216: 575-590. Shipboard Scientific Party, 2006. Proc. IODP, 10.2204/iodp.proc.304305.103.2006.

Poster II-74

Evolution of Magmatism During the Development of a Continental Metamorphic Core Complex

Konstantinou. Alexandros; Strickland, Ariel A.

Geological and Environmental Sciences, Stanford University, Stanford, CA

The Basin and Range Province (BRP) of the Western U.S. is a classic example of a broad, active, continental rift where structures related to differing amounts of extension can easily be studied for holistic models of the progressive extension of the brittle crust. Metamorphic core complexes represent windows into the processes that occur near or beneath the DBTZ, and are exhumed to the surface by the process of extension. Plutonic and volcanic rocks are often exposed within and around these complexes and are intimately linked to the extensional process, but the exact relationship is highly debated. This study focuses on the Cenozoic magmatic history of the Albion - Raft River - Grouse Creek Metamorphic Core Complex (ARG) and its relation to extensional faulting. The Raft River detachment fault is an impressive feature, with exposures of rocks which underwent ductile deformation extending for ~35 km in the transport direction of the detachment. Upper plate faults cut a thick stratigraphic/structural section and merge with this fault at depth. The map relations are such that together with geophysical data, the exposures of ductile crust can be projected beneath supracrustal sequences for a more accurate understanding of the large-scale geometry of the detachment system. Early magmatism in the Grouse Creek Mountains is represented by plutons and possibly volcanic rocks that range in age from 41 to 35 Ma (Egger et al., 2003; Brooks et al., 1995). This was followed by slightly younger magmatism, composed of granitic plutons that range in age between 30.4 and 25.3 Ma (Egger et al., 2003; Strickland et al., in press). These plutons represent large degrees of crustal melting and increasing T's of the crust through time, but mostly stalled at mid-crustal depths without erupting and predated the onset of actual Basin and Range extension. The latest magmatic event is composed of bimodal lavas - high temperature rhyolitic vitropheres and basalts- that are late Miocene in age (9.1 to 7.7 Ma), and up to 800 m thick, the Jim Sage volcanic suite. These lavas were erupted broadly during slip on the Raft River detachment which, based on thermochronology, was active during the Middle to Late Miocene (14 – 8.5 Ma) (Egger et al., 2003; Wells et al., 2000). The basin that originally formed by this fault system filled rapidly(?) with ~2000 m of Cenozoic sediments that are cut and displaced by younger, rotational normal faults, and strata now dip about 40 degrees to the west. The sedimentary section fines upward from a basal conglomerate to lacustrine deposits that record unroofing of footwall rocks and near its top is interleaved with the late Miocene Jim Sage volcanic suite that dips more gently (10-15 degrees) to the west and is cut only by small displacement normal faults.

Poster I-7

Noble Gases as Tracers of Mantle Deformation

<u>Kurz, Mark D.</u>; Warren, Jessica M.

M.D. Kurz, Marine Chemistry and Geochemistry, WHOI, Woods Hole, MA; J.M. Warren, Department of Terrestrial Magnetism, Carnegie Institution, Washington, DC

Due to their inertness and diverse isotopic compositions, the noble gases are extraordinary tracers of mantle sources, as well as diffusion and degassing processes. A recent study of ultramafic rocks from the Southwest Indian Ridge and St. Paul's Rocks (equatorial Mid Atlantic Ridge) suggests that noble gas abundances are strongly influenced by mantle deformation (Kurz, Warren, and Curtice, Chem. Geol. 266(2009)10-18). In both sample suites, the most deformed rocks (mylonites and ultramylonites) have the highest helium abundances when compared with related undeformed samples. The relationship between texture and helium abundance in peridotites suggests that metamorphism is an unrecognized but important control on noble gas distribution in the mantle and crust. The helium and neon isotopic compositions of the peridotites are primarily mantle-derived, which shows that the gases were incorporated at depth in the mantle, and are not strongly influenced by atmospheric gases. The St. Paul's Rocks mylonites have helium contents equivalent to gas-rich MORB glasses (6 x 10-6 to 3.8 x 10-5 cc STP He/gram), placing them among the most gas-rich mantle-derived rocks. He/Ne ratios in St. Paul's Rocks also vary widely (~ 20x) with deformation and mineralogy, with the highest He/Ne ratios (and helium concentration) found in the finest grained ultramylonite peridotite. Based on the He/Ne ratios, we infer that the most likely gas enrichment mechanism is diffusive trapping within defects at pressure in the mantle. This requires that deformation takes place under gas-rich conditions, and would have important implications for gas distribution in the mantle and crust, gas permeability of fault zones, and the preservation of ambient gas characteristics by deformation. Additional studies in different tectonic settings are presently under way to test the relationship between noble gases and deformation, and expore the use of noble gases as tracers of deformation.

Poster II-77

Fossil Bivalves in the Rainbow Area: New Insight into the Diversity and Evolution of Chemosynthetic Communities

Lartaud, Franck; **Little, Crispin T.S.**; de Rafelis, Marc; Bayon, Germain; Ildefonse, Benoit; Dyment, Jerôme; Le Bris, Nadine

L., Franck, Le Bris, N., Lab. Ecogéochimie des Environnements Benthiques (LECOB), FRE 3350, Observatoire Océanologique Banyuls sur Mer, UPMC Paris 06, Banyuls sur Mer, FRANCE; Little, C.T.S., School of Earth and Environment, University of Leeds, Leeds, UNITED KINGDOM; de Rafelis, M., Lab. Biominéralisations et Environnements sédimentaires, ISTeP, UMR 7193, UPMC Paris 06, Paris, FRANCE; Bayon, G., Départemet de Géosciences Marines, IFREMER, Plouzané, FRANCE; Ildefonse, B., Géosciences Montpellier, UMR 5243, Université Montpellier 2, Montpellier, FRANCE; Dyment, J., Lab. Géosciences Marines, UMR 7154, Institut de Physique du Globe de Paris, Paris, FRANCE

Hydrothermal circulation at ultramafic-hosted sites supports a large variety of high- and low-temperature hydrothermal vents and associated ecosystems. Along the Mid-Atlantic Ridge (MAR), different types of habitats for chemosynthetic-based organisms have been identified in a serpentinization context, e.g. the high temperature vents at Rainbow and Logatchev, and the low temperature, off-axis Lost City vents. Each displays a certain degree of isolation and endemic taxa. Much remains to be understood about the temporal dynamics and biogeography of these communities over geological time scales. During the MOMARDREAM_08 cruise (August 2008), numerous dead bivalve shells and associated carbonates were dredged from close to the active Rainbow vent field (36°N). These fossils point to past hydrothermal activity on top of a heavily sedimented ultramafic structure, 2.6 km east of the Rainbow field (site DR 9) at 24 ± 0.2 kyr, and on the slope of the same structure, 1.2 km north-east to Rainbow field (site DR 11) at 192 ± 12 kyr. At the younger site abundant shells of the vesicomyid bivalve genus Phreagena, previously unknown from the MAR, are distributed over a large area and associated with rarer specimens of the thyasirid bivalve Thyasira. At the older site, specimens of the mussel Bathymodiolus azoricus are abundant and co-occur with a few specimens of Phreagena and Thyasira. This diversity of bivalves is not seen in the living vent community at Rainbow.

The isotopic signatures of bivalve shells from both DR 9 and DR 11 suggest influence of oxidized methane on the sediment pore water DIC, which is consistent on Oceanic Core Complexes environments. There is a contrast between Phreagena shells, which are enriched in 13C, and Thyasira shells, which are highly depleted in 13C suggesting different mechanisms of carbon fixation for these bivalves. At off-axis sites like DR 9 and DR 11, both sediment cover and the availability of methane and sulphide, and possibly even hydrogen, as electron donors for autotrophic symbionts offer a wide variety of suitable habitats for chemosynthetic species. The spatial distribution and geochemical diversity of serpentine-hosted habitats might have favoured a more diverse fauna to colonize these habitats, and could have played a major role in the ability of chemosynthetic vent and seeps species to disperse over ocean basin scales.

Poster II-76

Rifting Mechanisms, Mantle Exhumation and the Initiation of Seafloor Spreading: Evidence from the Deep Galicia Basin

Lasseigne, Amy; Sawyer, Dale

Earth Science, Rice University, Houston, TX

Our study focuses on Iberia's Deep Galicia Basin (DGB) which formed by East-West rifting of Iberia from Newfoundland. The DGB is a magma-starved, fault-bounded block rifted margin basin. Because it is free from significant volcanic and salt deposits and has been relatively sediment starved over its history, the DGB is an ideal place to study rifting processes with both seismic and drilling technologies.

Several MCS seismic cruises, ODP and IODP drilling legs, and geophysical and submersible studies have developed a rich database along Iberia and its conjugate margin. Within the DGB, the crustal fault blocks and sediment are widely interpreted to overlie a prominent seismic reflection called

S. The basin's continental crust here is unusually thin, often less than 2 km thick over a wide area. Most interpretations make S a boundary separating the faulted and rotated continental crust from serpentinized upper mantle; and often, S is interpreted as the seismic expression of a major detachment fault. Given that, the extent and role of apparent low-angle faulting on this margin are still not fully understood. Proposed models for extension in the DGB vary from true low-angle detachment faulting, to rolling-hinge models, to polyphase faulting, or large-scale mass wasting. However, the current literature is based largely on the interpretation of east-west, dip oriented seismic profiles, and the complexity of this problem argues for a more 3D approach.

In this study, we utilize a grid of 2D seismic strike and dip lines over the well-developed S reflector area in order to examine the along-strike variation of the margin. The profiles are processed using Prestack Kirchhoff Depth Migration and a layer stripping approach with the hope of extracting true geometries and dips. Focusing on two North-South profiles overlying S, we have already made a few surprising observations. For one, the geometries of some crustal fault blocks seem strangely "pod-shaped" when looking at individual strike lines. The fault blocks therefore do not seem elongated parallel to the margin but highly broken up in both dimensions. Also, the amount of pre-rift sediment making up the stretched continental crust is greater than expected, often making up the entire thickness of crust and lying in direct contact with S. S itself has a more irregular geometry than previously realized, having large steps which often correlate to the edges of the crustal rotated fault blocks. Other smaller steps in S appear unrelated to the crust above, but rather associate with a series of north-dipping reflections beneath S. These reflections below S could be interpreted as seaward dipping reflectors, but there are two problems with that interpretation: 1) their apparent northward dip is not in agreement with the expected east-west extension, and 2) these reflections lie in material that is most commonly interpreted as serpentinized upper continental mantle. With further examination we hope to describe these sub-S reflections with length, true dip, and S-offset; map out S's geometry in space; quantify extension in both dimensions; and compare findings to existing extension models for the Deep Galicia Basin.

Poster I-29

From Mantle to Microbes: The Cycling of Volatiles in Ridge Environments

Lilley, Marvin D.; Frueh-Green, Gretchen L.

M.D. Lilley, University of Washington, Seattle, WA; G.L. Frueh-Green, ETH-Zurich, Zurich, SWITZERLAND

There are fundamental differences in the nature of the volatiles produced in basaltic and ultramafic-hosted hydrothermal systems. Olivine-rich gabbros and mantle peridotites are significant components of the seafloor in slow- and ultraslow-spreading ridge environments. The alteration of these rocks has fundamental geophysical and biogeochemical consequences for the global marine system and is critical in cycling reduced volatiles from the mantle to the biosphere. Thus, it is important to understand the extent and conditions of alteration (e.g., temperature, fluid flux, oxidation states) and the impact of these processes for the formation and speciation of C-O-H-S fluids as nutrients for biological activity. Emphasis will be placed on how fluid chemistries in peridotite-hosted hydrothermal systems (Rainbow, Logatchev, Lost City and Saldanha along the MAR) differ from those in black smoker systems, and on the role of serpentinization in generating highly reduced, volatile-rich hydrothermal fluids and in the biological communities they may support. Serpentinization produces elevated concentrations of primarily abiogenic methane (up to 2.5 mmol/kg) and hydrogen (up to 16 mmol/kg) that have important consequences for vent microbial communities and for the existence of a deep H2-based biosphere. Varying fluid fluxes influence redox conditions and the stabilities of oxides, sulfides, and FeNi alloys, which together with microbial activity, can significantly affect C-H-S cycles in these systems. In addition, recent experimental studies and vent fluid data provide evidence for abiotic synthesis of organic acids and other organic compounds through Fischer-Tropsch type reactions during serpentinization and provide constraints on alternative pathways for the formation of early membranes and the origin of life. At moderate temperatures, such as at Lost City, serpentinization produces high pH fluids that promote carbonate precipitation and produce large, porous hydrothermal structures. The fluids in this system contain high concentrations of H2 and CH4 but very low concentrations of CO2.This production of reduced volatiles and variable mixing with ambient seawater in the subsurface and in near-vent environments is an important process in creating strong chemical gradients that provide micro-niches for distinct communities of H-, S- and CH4-utilizing archaea and bacteria which also results in high organic carbon contents (up to 1 wt%) in the hydrothermal structures.

In contrast, basalt-hosted hydrothermal fluids typically contain much higher concentrations of CO2 and relatively lower concentrations of H2 and CH4. The exception to this generalization is that during (and for a short period after) eruptions, basaltic-hosted fluids can exhibit very high H2 (up to 40 mmol/kg) concentrations, higher than any yet seen in ultra-mafic systems. Volatile concentrations and isotopic signatures from several basalt hosted mid-ocean ridge environments will be compared and contrasted with those from the ultra-mafic hosted systems mentioned above.

Poster II-47

Godzilla Mullion: Plagioclase Systematics of a Back-arc Core Complex

Loocke, Matthew P.; Snow, Jonathan E.; Ohara, Yasuhiko

M.P. Loocke, J.E. Snow, Earth and Atmospheric Sciences, University of Houston, Katy, TX; Y. Ohara, Hydrographic and Oceanographic Department of Japan, Tokyo, JAPAN

Godzilla Mullion is the largest known example of a large low-angle oceanic detachment fault, or Oceanic Core Complex (OCC). It is located in the back arc of the Izu-Bonin-Mariana (IBM) system, at the southern tip of the Parece Vela Rift in the Philippine Sea and covers an area measuring roughly 125km by 55km. A total of 11 academic expeditions have been conducted in the area, including two recent dredging cruises and a submersible dive cruise on the megamullion itself. Peridotites recovered from the mullion are divided petrographically into Fertile, Depleted, and Plagioclase-bearing groups (1). Plagioclase rimming spinel (or rather its low temperature pseudomorphs) is a strong indicator of melt stagnation in the lithosphere (2). For this reason, the extant thin section collection was surveyed to determine the prevalence and geographic distribution of melt impregnation on Godzilla Mullion. A total of 178 thin sections were studied from the Kairei KR 03-01, Hakuho Maru KH 07-09 and Yokosuka YK 09-05 cruises. In these, 45.56% of all peridotites were found to be plagioclase bearing. This compares with the worldwide abyssal peridotite average of ~20%(2). The mullion is divided up into three regions, the proximal region (closest to termination), the medial region, and the distal region (furthest from the termination)(3).Observations by region provide that 53.45% (62 out of 116 samples) in the proximal region (15 dredges), 11.76% (2 out of 17 samples) in the medial mullion(3 dredges), and 25% (7 out of 28) in the distal mullion (5 dredges) show of evidence of plagioclase impregnation. Unpublished major element compositions of spinels from the samples studied support these plag-systematics. The distal, depleted portion of the mullion represents a robust mantle section that was still producing abundant melt and can be compared to typical oceanic spreading with its relatively "normal" percentage of plag impregnation. The medial, fertile portion of the mullion represents a steep falloff in melt productivity, to a minimum of about 5%(4). The proximal, heavily plag-impregnated portion of the mullion represents an increasing stagnation of melt into a lithosphere that was progressively thickening. This coincides with a change in character of the massif surface in the proximal region from a domed striated mullion surface to a massive, slab-type exhumation more typical of ultraslow spreading ridges.

(1) Ohara, et al., (2003) G3. 4 (7), 8611, 10.1029/2002GC000469.
(2) Dick (1989) Geol Soc. Lond. Spec. Pub. 42:71-105.
(3) Ohara, et al., (2009), Eos Trans. AGU, 90(52), Fall Meet. Suppl. Abst.Num. T33D-06
(4) Hellebrand, et al., 2001 Nature

Poster I-33

Petrogenesis of Piemont-Ligurian Oceanic Plagiogranites (Albitites), Western Alps

Ma, Changqian; Guillot, François; Chen, Ling

C. Ma, L. Chen, State Key Laboratory of GPMR, China University of Geosciences, Wuhan, Hubei, CHINA; C. Ma, F. Guillot, Géosystèmes FRE 3298, Université Lille 1, CNRS-Lille 1, SN5, F-59655 Villeneuve d'Ascq Cedex, Lille, FRANCE

The European Alps recorded the closure history of several ocean basins during the convergence between African Plate and European Plate and it is classically proposed that the Alps are the products of two orogenies, a Cretaceous one followed by a Tertiary one. The former is related to the closure of an embayment of the Meliata ocean into Apulia, while the latter is due to the closure of the Alpine Tethys between Apulia and Europe (Schmid et al, 2004). Here we report recent field research on the ophiolite suite located between Montgenèvre (SE France) and Serra del Parco (NW Italy).

The Montgenèvre-Serra del Parco ophiolite originated as an oceanic crust fragment of Piemont-Ligurian ocean (a segment of the Mesozoic Tethys ocean). This ophiolite suite was exposed to surface before the Alpine orogeny or during its earliest stage, as testified by fission-track ages (Schwartz et al, 2007) on zircon (118±1 Ma) and on apatite (67±9 Ma). Unlike most other ophiolites in the Alps, Montgenèvre-Serra del Parco rocks didn't undergo strong ductile deformation and metamorphism during the Tertiary Alpine orogeny. This ophiolite comprises serpentinized peridotite, gabbro and pillow lavas, and was intruded by diorite and albitite veins/dikes. This rock assemblage is not consistent with the typical mid-ocean ridge extension model, since neither a continuous and thick basaltic layer nor a true sheeted-dike complex ever existed (Lemoine et al, 1987). This phenomenon has been attributed to the asymmetric development of a dipping detachment fault which resulted in mantle denudation.

The albitite is composed of albite (90%), hornblende (tremolite - actinolite), minor quartz, and accessory minerals including allanite, apatite and zircon. Petrogenesis of albitites is highly controversial. It is suggested that these albitites represent partial melts of gabbros and diorites during oceanic crust detachment based on the following facts: (1) compared with the extensive ductile deformation of serpentinized peridotite, gabbro and diorite, the albitite has typical fine-grained magmatic texture preserved from ductile deformation; (2) the albitite veins always cut through mylonitized gabbros; (3) the zircon U-Pb age (148±2Ma) of the albitites is younger than the crystallization ages of diorites (zircon U-Pb age, 156±3Ma) and gabbros intruded into the mantle peridotites (whole rock Sm-Nd isochron age, 198±22Ma)(Costa and Caby, 2001); (4) According to the Al/(Mg+Fe) vs. Ca/(Mg+Fe) diagram (Altherr et al, 2000), the albitite has similar chemical features with products of partial melting of mafic rocks. These data indicate that the albititic melt is formed after the emplacement of the ophiolite suite. It is suggested that we should be prudent when employing the age of oceanic plagiogranite or albitite as ophiolite emplacement age or oceanic crust age.

This study is financially supported by the Key International S &T Cooperation project of China (2007DFA21230), China Geological Survey(Grant 1212010918002) and the Nature Science Foundation of Hubei Province (2009CDA004). Nicolas Tribovillard, while he was leader of the Géosystèmes Research team, has funded our field travels.

Poster II-55

Detachment Faulting and Melt Transport through the Mantle Lithosphere: Evidence from the Lizard ophiolite, SW England

MacLeod, Christopher C. J.

School Earth & Ocean Sciences, Cardiff University, Cardiff, UNITED KINGDOM

The Lizard Complex is a dismembered Devonian ophiolite that forms one of a series of thrust nappes within the Variscan belt of SW England. Within the largest contiguous thrust sheet it preserves mantle peridotites, a 'Moho' transition into a gabbroic sequence and thence the base of a sheeted dyke swarm with N-MORB composition. The Lizard Complex is thought to have formed in a small incipient ocean basin, probably close to a magma-poor ocean-continent transition, broadly analogous to the tectonic setting inferred for the Mesozoic Alpine Tethyan ophiolites. Metre-scale mylonitic shear zones within gabbros in the mantle-crust transition zone are cut by chilled MORB dykes, documenting exhumation and uplift on the seafloor. Cross-cutting relations between dyke sets are consistent with rotation on ridge-parallel structures with the same kinematics as the mylonites (Roberts et al., 1993, EPSL 116, 101-112). Within the mantle section stratigraphically beneath the mantle-crust transition is a major mylonite shear zone that displays the same orientation and kinematics as the smaller-scale structures above, and is hence (accounting for the tilting of the nappe) interpreted as a ridge-parallel structure with normal displacement. This, the Carrick Luz shear zone, is a 200m-wide zone of intensively and pervasively deformed gabbro mylonite that forms a dyke-like body within undeformed mantle peridotite. Xenoliths of peridotite within the gabbro mylonite demonstrate that the gabbro is a mafic intrusion into the peridotite. Within the shear zone a continuum of fault rocks from discrete ultramylonite shear planes through to cataclasites and fault gouges, all with the same kinematics, attests to progressive exhumation on the structure. Chilled MORB dykes cross-cut the shear zone and demonstrate that the deformation occurred on the ocean floor. Following Allerton & MacLeod (1998, Geol. Soc. London Spec. Publ. 148, 29-42), I interpret the Carrick Luz shear zone as a plate boundary-scale, ridge-parallel detachment fault within the mantle lithosphere beneath the Lizard spreading axis, into which ascending mafic melt was intruded and channelled, and onto which deformation was thereby efficiently localised. Capture and channelling of melt by detachment faults, as inferred here, provides a mechanism for efficiently weakening the lithosphere beneath the ridge axis, and demonstrates how detachment faults may control melt transport through the mantle lithosphere.

Poster II-58

Life Cycle of Oceanic Core Complexes, 2: Melt Emplacement and Detachment Fault Termination Mechanisms

MacLeod, Christopher C. J.; Searle, Roger; Murton, Bramley

C.J. MacLeod, School Earth & Ocean Sciences, Main Building, Cardiff University, Cardiff, UNITED KINGDOM; B. Murton, National Oceanography Centre, Southampton, UNITED KINGDOM; R. Searle, Earth Sciences, Durham University, Durham, UNITED KINGDOM

By means of a near-bottom sidescan sonar, bathymetry and sampling study of active oceanic core complexes (OCCs) on the Mid-Atlantic Ridge in the 13°N region we examine the controls on formation, evolution and subsequent termination of large-offset detachment faults at slow-spreading mid-ocean ridges. In this contribution we focus on the role of melt supply and mechanisms of melt emplacement in controlling how OCCs are terminated. We have quantified the relative contribution of tectonic and magmatic spreading by systematically measuring heaves on faults as far as magnetic anomaly C2n, and show that OCC formation is triggered by a reduction in magma supply relative to the symmetrically-spreading inter-OCC regions. Whereas the inter-OCC regions have robust neovolcanic zones, volcanism is suppressed or absent on the hanging walls of the active OCCs. This suggests that plate separation becomes focused onto the active detachment faults, an assertion supported by dating and/or magnetic studies of OCCs elsewhere, which show that the extension accommodated by the OCC detachments is consistently in excess of half the total plate separation. Under such circumstances the detachment must lengthen with time and the active (sub-surface) portion of the fault must therefore migrate progressively towards the axial valley and, ultimately (at least at depth) across it, and past the adjacent neovolcanic zones. This necessary geometrical evolution has significant implications for the nature of melt emplacement into the lithosphere. In the near-symmetrically spreading regions new melt is emplaced into the hanging walls of the valley-wall faults, in the centre of the axial valley. In contrast, once an active detachment migrates across the axial valley at depth, melt delivered to the axis here (either laterally or from below) will instead be preferentially intruded into the footwall of the OCC detachment. We propose that, at this stage in the evolution of an OCC, the mechanism of magma emplacement into the lithosphere must change fundamentally. From this time onwards variations in the flux of melt delivered from the mantle become decoupled from the magmatic component of seafloor spreading, and melt addition instead contributes to the velocity of the plate on the OCC flank. This 'footwall capture' mechanism of melt emplacement can explain the common observation of gabbro plutons in exposed OCC detachment footwalls. An OCC detachment is ultimately terminated when the flux of melt delivered to the footwall is sufficient to overwhelm it. This may not necessarily be related directly to a temporal increase in mantle melt supply, but to the spatial and temporal focusing of magma within the footwall. OCCs in the 13°N region are in the process of being terminated today by the along-strike propagation of the neovolcanic zones from the inter-OCC regions, demonstrating that lateral redistribution of melt along axis, presumably by dyking, is an efficient mechanism for terminating detachments.

Poster II-56

Quantitative Constraint on Tectonic Rotations at Oceanic Core Complexes From a Structural and Palaeomagnetic Study of Oriented Rock Cores From the Mid-Atlantic Ridge at 15°45′N

MacLeod, Christopher C. J.; Carlut, Julie; Escartin, Javier; Horen, Hélène; Morris, Antony

C.J. MacLeod, School Earth & Ocean Sciences, Cardiff University, Cardiff, UNITED KINGDOM; J. Carlut, Laboratoire de Géologie, Ecole Normale Supérieure de Paris, Paris, FRANCE; J. Escartin, Laboratoire de Géosciences Marines, Institute de Physique du Globe de Paris, Paris, FRANCE; H. Horen, Département de Géologie, Université de Picardie Jules Verne, Amiens, FRANCE; A. Morris, School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, UNITED KINGDOM

The sub-surface geometry of detachment faults at slow-spreading mid-ocean ridges is debated: are they planar features that form and slip at low angles, as often inferred for their continental equivalents, or do they initiate at steep angles and then flatten in response to flexural unloading as displacement proceeds, as predicted in 'rolling hinge' conceptual models? An essential difference is that significant rotation of the footwall should occur in the rolling hinge but not the planar fault model. This can be tested using palaeomagnetism. Previous attempts to address this question have relied upon interpretation of azimuthally unoriented drillcores, from which only the inclinations of remanences can be considered. Anomalous inclinations have been put forward as evidence for substantial rotations about horizontal ridge-parallel axes. Although plausible, these interpretations are very non-unique: a rotation about an axis of any orientation can generate the inclination changes observed, and most of these solutions require only small rotation magnitudes. We here present palaeomagnetic and structural data from a unique set of azimuthally oriented cores, collected using the 'BRIDGE' seabed rock drill, from the 15°45′N oceanic core complex on the Mid-Atlantic Ridge. From these we quantitatively constrain the permissible axes and magnitudes of rotation of the detachment fault footwall without a priori assumption about the orientation of the axis. We show that significant rotations (64° ±16°) have indeed occurred, about a sub-horizontal, near ridge-parallel axis, consistent with the previous inferences, and robustly supporting the rolling hinge models. We further discuss the geological implications of this result for the structural, magmatic and thermal history of the 15°45'N massif and inferences for oceanic core complexes in general.

Poster II-59

Life Cycle of Oceanic Core Complexes, 3: Crustal Structure and Melt Supply Variability on the Mid-Atlantic Ridge at 13N

Mallows, Christopher; **Searle, Roger**

Earth Sciences, Durham University, Durham, UNITED KINGDOM

We present the results of a combined deep-towed sidescan sonar and magnetic survey with shipboard gravity and extensive seafloor sampling across active Oceanic Core Complexes on the Mid-Atlantic Ridge between 13N and 14N. Sidescan sonar data have been mapped to reveal variability in the width of the neo-volcanic zone (NVZ), which is entirely absent opposite active OCC formation. Furthermore, the youngest volcanic material (identified from sidescan and magnetic data) exists in close proximity to the axial valley-wall faults, suggesting these faults may capture upwelling melt at depth and transport it away from the ridge axis. In some instances there is a mismatch between the location of the NVZ and central magnetic anomaly high, which can be explained by temporal variations in the locus of melt emplacement. Geomagnetic polarity transition widths show this zone of emplacement to vary along-axis between 2 and 5 km wide. 3D modelling of the gravitational residual mantle Bouguer anomaly (RMBA) indicates that OCCs are associated with high density (~2900 kg.m3) material at shallow depth. The overall RMBA

structure is remarkably similar to that which is observed at Kane Massif and Fuji Dome. In addition, circular lows are observed within the RMBA along the ridge axis, suggesting discrete centres of melting. On the flanks conjugate to active OCCs, RMBA highs are observed which show that significant reductions in melt emplacement are recorded on both plates.

Oral – Tuesday 11th, 14:45

The Role of Detachment Faults During Crustal Thinning, Mantle Exhumation and Continental Break-up at Magma-poor Rifted Margins?

Manatschal, Gianreto; Lavier, Luc

G. Manatschal, UdS-CNRS, IPGS-EOST, Strasbourg, FRANCE; L. Lavier, UTIG, Jackson School of Geosciences, Austin, TX

Extensional detachment faults are widely regarded as playing an important role in explaining extreme crustal thinning, mantle exhumation and continental break-up at magma-poor rifted margins. However, how important are these structures, when and how do they form, how well can they account for geological and geophysical observations made along deep-water rifted margins, and how can they be compared with continental and oceanic core complexes? Mapping of rift-related detachment faults at the present-day Iberia-Newfoundland and the ancient Western Pyrenees-Bay of Biscay and Alpine Tethys rifted margins shows that these structures are complex and can not be described by one single low-angle detachment fault as commonly shown in the classical Wernicke type simple shear models. Detachment faults form in brittle layers and are interacting with decollements in ductile layers in the crust. Only when the crust is thinned to less than 10 km and the whole crust is brittle, detachment faults can cut from the surface into mantle. Fluids are intimately linked with detachment faulting and are responsible for the breakdown and hydration of feldspar and olivine resulting in weak fault zones that can localize deformation and modify the bulk rheology of the extending brittle layers. Although detachment faults occur in the crust, they seem to be more prominent in the ocean continent transition of magma-poor rifted margins, where they can explain the occurrence of subcontinental mantle over tens to hundreds of kilometres separating continental crust from oceanic crust. In conclusion, extensional detachment faults observed at rifted margins are by far more complex as previously proposed in the existing models. Detachment faults are polyphase structures that occur in the highly extended and hydrated parts of the brittle crust and upper mantle. The formation of detachment faults seems to be strongly linked with the bulk rheological evolution of the extending lithosphere that depends on the initial composition, thermal structure, presence of fluids and magma and other factors. How these factors control the strain distribution and how they evolve in time and space during rifting is, however, not yet understood and remains the subject of ongoing research.

Oral – Sunday 9th, 09:45

Hydrothermal Systems and Detachment Faulting

McCaig, Andrew

Institute of Geophysics and Tectonics, School of Earth and Environment, University of Leeds, LS2 9JT, UNITED KINGDOM

It has long been recognised that black smoker hydrothermal systems on slow spreading ridges are larger, longer lived, and have higher heat outputs than those on fast spreading ridges. A number of active hydrothermal systems in the Atlantic occur several km away from the neovolcanic zone (NVZ) and have been linked to detachment faulting. These hydrothermal systems challenge classical assumptions about the depth of hydrothermal circulation, the permeability structure of the crust and upper mantle, and the causal relationships between magmatism, tectonics and hydrothermal circulation. Detachment-related hydrothermal systems can be divided into three types: (1) Black smoker systems located on the hangingwall of detachments (eg. TAG); (2) Black smoker systems located on exposed detachment fault surfaces (Logatchev, Ashadze, Rainbow); (3) Low temperature systems located on exposed detachment fault surfaces (Lost City).

TAG is located in basaltic rocks about 4.5 km east of the neovolcanic zone. On the basis of microseismicity, the vent field is inferred to be underlain by a west-dipping convex-upward detachment fault which steepens to 70°

beneath the NVZ. Fluid is inferred to be channelled up the fault from gabbroic intrusions at 7 kmbsf. TAG has an estimated heat output of 1000 MW, which is too large to be easily maintained in steady state, and there is geochronological evidence for episodic behaviour over more than 100kyrs. Fluid flow up detachments is supported by studies of exposed (inactive) detachment faults, which commonly show talc-tremolite-chlorite assemblages and strong isotopic alteration consistent with high fluxes of seawater-derived fluid at black smoker temperatures. In contrast, there is little evidence for high fluid fluxes in detachment fault footwalls, although hydration over a range of temperatures is observed.

Type 2 systems are more difficult to explain, particularly Rainbow, which has a very high heat output and is thought to have been active for the last 8-12,000 years on the basis of sediment profiles. Rainbow is situated on a probable detachment fault at a non-transform offset, and appears to be localised by steep faults cutting the detachment. Clearly, fluid circulation occurs in the ultramafic footwall, and not in the detachment fault itself. Unfortunately, neither passive nor active seismic experiments have been conducted on type 2 systems, and the internal structure of the detachment footwalls, location of active deformation, and the location of any magma chambers are all conjectural.

The Lost City Field (Type 3) is superimposed on the deformation and metamorphism characteristic of detachment faulting, and vents at much lower temperatures. The main role of detachment faulting appears to be in bringing serpentinising mantle rocks containing 9and possibly releasing) significant heat close to the sea floor, although topographic effects related to core complex formation may also be important.

Detachment faults can be divided into two endmembers, a high temperature type characterised by extensive mylonites formed at 800-950 °C (e.g. Atlantis Bank, SWIR), and a low temperature type characterised by talc-tremolite-chlorite-serpentine schists and an absence of mylonitic deformation in the footwall (30° N and 15°-45′ N, Atlantic). A simple 1-D thermal model shows that if a detachment is the locus for discharge of fluids at black smoker temperatures, as in the TAG model above, rapid cooling below the brittle-ductile transition (700-750 °C) will occur in the upper 1-2 km of the footwall, suppressing mylonite development. Thus hydrothermal circulation could have a profound influence on ridge crest rheology and tectonic style. A model is presented in which hydrothermal circulation drives the depth of magma emplacement downward into the footwall of a steep low-displacement fault, triggering a change to (cold) detachment faulting as magma is trapped beneath the fault.

Poster II-53

The Role of Strain Partitioning in the Development of an Oceanic Detachment Fault System: Insights From Relict Oceanic Core Complexes in the Western Mirdita Ophiolite, Albania

Miranda, Elena; Johnson, John; Dilek, Yildirim

E. Miranda, J. Johnson, Geological Sciences, California State University Northridge, Northridge, CA; Y. Dilek, Geology, Miami University, Oxford, OH

We use microstructural and EBSD analyses to evaluate the strain localization processes that accommodate oceanic detachment faulting in the Krabbi and Puka relict oceanic core complexes of the middle Jurassic Western Mirdita Ophiolite, Albania. Mantle peridotites, lower crustal gabbros, and amphibole schists are exposed along the surfaces of the dome-shaped Krabbi and Puka massifs and comprise the structurally shallow portions of the footwall of an oceanic detachment fault system. These footwall rocks are separated from the upper crust volcanic rocks in the hanging wall by an oceanic detachment fault that crops out along the topographic base of the dome-shaped massifs. We document fabric development in the footwall rocks exposed along the massif surfaces to evaluate the role of strain partitioning in the development of a localized oceanic detachment fault. Abundant melt-impregnated lherzolitic peridotites are overprinted by laterally extensive granulite-grade mylonitic fabric development, and less abundant gabbroic rocks with rare magmatic and granulite- and amphibolite-grade mylonitic fabrics occur close to an intrusive contact with the peridotites. Tremolite-chlorite schists with relict pyroxene are interlayered with spinel-bearing peridotite mylonites, and are found in a 100 m-thick zone of semibrittle deformation in the uppermost part of the footwall beneath the detachment fault surface. The peridotite fabrics in the footwall suggest that melt intrusion (impregnation) was closely followed by extensive high-temperature ductile deformation, and the rare magmatic and mylonitic fabrics in the gabbros indicate that this high-temperature deformation may have been preferentially accommodated within the peridotites during the earliest stage of detachment faulting. The interlayered schists and peridotite mylonites are indicative of semibrittle deformation, which was preferentially accommodated within peridotites during this later stage of detachment faulting, and was promoted by fluid flow along the shear zones associated with detachment faulting. Our results suggest that strain localization associated with detachment faulting may be partitioned into the lithological units that constitute a greater proportion of the footwall, and that fabric development in the less abundant footwall units may be restricted to those rocks near unit contacts owing to rheologic contrasts between different rock types.

Poster I-15

Direct Observations of the 25°S Oceanic Core Complex Along the Central Indian Ridge

Morishita, Tomoaki; Soda, Yusuke; Sawaguchi, Takashi; Nakamura, Kentaro; Okino, Kyoko; Takai, Ken; Kumagai, Hidenori

T. Morishita, FSO, Kanazawa Univ., Kanazawa, JAPAN; Y. Soda, Dep. Earth Sci., Waseda Univ., Tokyo, JAPAN; T. Sawaguchi, Natural Sci. Lab., Toyo Univ., Tokyo, JAPAN; K. Nakamura, Precambrian Eco. Lab., Jamstec, Yokosuka, JAPAN; K. Okino, Ocean Res. Inst., Univ. Tokyo, Tokyo, JAPAN; K. Takai, SUGAR, JAMSTEC, Yokosuka, JAPAN; H. Kumagai, IFREE, JAMSTEC, Yokosuka, JAPAN

We directly observed and recovered samples along a transect from near the termination extending towards the breakaway of an oceanic core complex, 23 km x 13 km in size, along the Central Indian Ridge at 25°S (25OCC), where the spreading rate is about 50 mm/year, using SHINKAI 6500 of the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). The bathymetric corrugations with wavelengths of ~1-1.5 km and striations at centimeter-scale parallel to the spreading direction are well developed in the 25OCC. Samples recovered from the 25OCC were basalts (doleritic rocks), gabbros, granites, serpentinized peridotites and their deformed equivalents. Highly deformed rocks, cataclastic breccias to mylonitic schists were restrictedly recovered from the sheet-like structures on the top surface of the 25OCC whereas less deformed rocks were recovered from the immediately beneath the top surface. Basaltic samples beneath the top surface have undergone variable degrees of alteration and weathering. The gabbros (olivine gabbro, gabbro, gabbro norite, and oxide-rich gabbro) have magmatic textures, usually no or very minor plastic deformation except for very localized millimeter-scale altered zones of tremolite/actinolite and/or chlorite. Less deformed, granular serpentinites were recovered along the ridge-facing slope. Samples recovered from the top surface of the 25OCC show that the striated features are associated with high-strain cataclastic breccias to mylonitic schists of peridotites, gabbros, basalts and their combination origin. Talc occurs as two different textures: static replacing primary minerals, and syn-deforming textures showing shape-preferred orientations, i.e., talc schists. It should be emphasized that peridotitic clasts in serpentine/talc schists show mylonite texture characterized by reduction of olivine grain size and elongated orthopyroxene grains. Gabbroic clasts also display the mylonite textures characterized by grain size reduction of plagioclase. Tremolites/actinolites are abundant in well-foliated, altered gabbros. Basalts inhomogeneously suffered from chloritization. Breccias, consisting of many kinds of clasts and their-derived minerals in the matrix of tremolite/actionlite, chlorite or talc, develop micro-faults with preferred orientations. Our study revealed that gabbros and peridotites were tectonically exposed as oceanic core complexes in the intermediate-spreading ocean ridges. Detachment might initiate in ductile regime of peridotites and gabbros, probably around the Moho. Hydrothermal fluids were locally infiltrated along the fault plane during the deformation, resulting in the formation of secondary hydrous minerals. Strain localization along the fault plane was enhanced by the presence of the secondary hydrous minerals. The talc-rich deformed rocks were probably formed by reactions between serpentinites and mafic rock-derived, SiO2-rich hydrothermal fluids. Deformation continued to occur in the brittle regime at low temperatures during the exhumation, resulting in platy landform with lineations.

Poster II-66

Palaeomagnetic Constraints on the Evolution of the Atlantis Massif Oceanic Core Complex (Mid-Atlantic Ridge, 30°N)

Morris, Antony; Pressling, Nicola; Gee, Jeffrey; John, Barbara E.; MacLeod, Christopher J.

A. Morris, N. Pressling, School of Geography, Earth & Environmental Sciences, University of Plymouth, Plymouth, UNITED KINGDOM; J. Gee, Scripps Institution of Oceanography, University of California (San Diego), La Jolla, CA; B.E. John, Department of Geology & Geophysics, University of Wyoming, Laramie, WY; C.J. MacLeod, School of Earth & Ocean Sciences, Cardiff University, Cardiff, UNITED KINGDOM; N. Pressling, School of Ocean & Earth Science, University of Southampton, Southampton, UNITED KINGDOM

IODP Expedition 304/305 sampled a 1.4 km faulted and complexly layered footwall section on the central dome of the Atlantis Massif oceanic core complex. The core (Hole U1309D) is dominated by gabbroic lithologies with minor ultramafic rocks and reflects the interplay between magmatism and deformation prior to, during, and subsequent to a period of footwall displacement and denudation associated with slip on an oceanic detachment fault. Palaeomagnetic analyses of the gabbroic sequences at Atlantis Massif provide valuable information on the evolution of the section. High unblocking temperature components of reversed polarity are seen throughout the gabbroic sequences. In a number of intervals, however, the gabbros exhibit a complex remanence structure with the presence of lower temperature normal and reversed polarity components, suggesting an extended period of remanence acquisition during different polarity intervals. Remanence characteristics suggest that these multicomponents were acquired by a thermal mechanism. However, there appears to be no correlation between remanence structure and either the igneous stratigraphy or the distribution of alteration in the core. Instead, the remanence data are consistent with a model in which the footwall section acquired magnetizations of different polarity during a protracted cooling history spanning two geomagnetic reversals. Subtle differences in magnetite grain sizes appear to have controlled the temperature range and number of components recorded by different samples. These data are used as a marker for tectonic rotation of the footwall section in order to address the debate over the sub-surface geometry of oceanic detachment faults. Competing models involve either: (a) displacement on planar, low-angle faults with little tectonic rotation; or (b) progressive shallowing by rotation of initially steeply dipping faults as a result of flexural unloading (the "rolling-hinge" model). This simple test is limited, however, by the lack of full palaeomagnetic vectors, since only magnetic inclination data are normally available from unoriented ODP/IODP drill core samples. For the first time we have overcome this limitation by independently reorienting core pieces to a true geographic reference frame by correlating structures in individual pieces with those identified from oriented imagery of the borehole wall. This allows reorientation of paleomagnetic data and subsequent tectonic interpretation without the need for a priori assumptions on the azimuth of the rotation axis. Results indicate a 46°±6° counterclockwise rotation of the footwall around a MAR-parallel horizontal axis trending 011°±6°. This provides unequivocal confirmation of the key prediction of flexural, rolling-hinge models for oceanic core complexes, whereby faults initiate at higher dips and rotate to their present day low angle geometries.

Oral – Sunday 9th, 09:00

Palaeomagnetic Insights into Oceanic Detachment Fault Processes at Mid-ocean Ridges

Morris, Antony

School of Geography, Earth & Environmental Sciences, University of Plymouth, UNITED KINGDOM

Palaeomagnetic remanence directions have been used as markers for tectonic rotation in numerous studies of oceanic crustal geodynamic processes. In ophiolite terranes, a combination of three-dimensional exposures, fully oriented palaeomagnetic samples, and supporting field structural data allows rotations to be quantified even in areas that have experienced complex tectonic histories (e.g. sequential seafloor spreading-related and emplacement-related deformation events). By contrast, palaeomagnetic analysis of oceanic rocks collected by ODP/IODP drilling is hampered by azimuthally unoriented core samples and a reduced scope for structural characterization. Under these circumstances, unique tectonic interpretations are impossible and a number of assumptions must be made in order to analyse palaeomagnetic inclination data, including *a priori* selection of an axis of rotation.

Nevertheless, remanences have been used to infer whether detachment fault footwall sections have experienced rotation during displacement in several oceanic core complexes (OCCs), including: Atlantis Bank (Southwest Indian Ridge; ODP Legs 118 and 176), Fifteen-Twenty Fracture Zone (Mid Atlantic Ridge (MAR); ODP Leg 209 & JR63 cruise), the MARK area (MAR; ODP Leg 153) and Atlantis Massif (MAR; IODP Expedition 304/305). Rotations are invoked to explain differences between the mean palaeomagnetic inclination and the expected axial geocentric dipole value at the sampling site, but the amount of rotation depends critically on the choice of rotation axis. These uncertainties even extend to cases where there is no significant difference between observed and expected inclinations, as substantial rotation may still have occurred around a rotation axis oblique to the expected direction (resulting in initial steepening and subsequent shallowing of the magnetic vector back to its unrotated inclination).

Robust quantification of detachment footwall rotation therefore requires knowledge of both palaeomagnetic inclinations and declinations. An approach adopted recently at Atlantis Massif OCC is to independently restore IODP core pieces to their original azimuths by correlating core structures with features seen on oriented geophysical imagery of the borehole wall. This provided the first fully oriented palaeomagnetic dataset from a section of lower oceanic crust, and demonstrated that the Atlantis Massif detachment fault initiated at a steep dip of c. >50° and progressively rotated to lower angles during displacement. Such footwall rotation has also been demonstrated definitively at an OCC associated with the Fifteen-Twenty Fracture Zone, where fully oriented 1 m cores have been obtained using the BRIDGE sea-bed rock drill system (confirming an earlier, inclination-only-based interpretation of data from ODP Leg 209). In this case, integration of palaeomagnetic data with structural kinematic data obtained from the same oriented cores provides a powerful method for simultaneously quantifying both the amount and axis of rotation and their associated uncertainties.

Finally, palaeomagnetic analyses of ODP/IODP samples from the MARK area and Atlantis Massif have identified unique examples of young, lower crustal gabbros that record complex, multicomponent remanences acquired in different geomagnetic polarity chrons. Thermal demagnetization of these remanences yields important information on permissible OCC footwall temperatures at chron boundaries in these sections. In conjunction with constraints from radiometric dating and closure temperatures, these data can provide valuable constraints on footwall cooling histories.

Poster I-16

Godzilla Mullion Developed in a Slow-spreading Environment: New Age and Petrologic Data Constraints

Ohara, Yasuhiko; Snow, Jonathan E.; Ishizuka, Osamu; Tani, Kenichiro

Y. Ohara, Hydrographic and Oceanograph Department of Japan, Tokyo, JAPAN; Y. Ohara, O. Ishizuka, K. Tani, Institute For Research on Earth Evolution, Japan Agency for Marine-Earth Science and Technology, Yokosuka, JAPAN; J.E. Snow, Department of Geosciences, University of Houston, Houston, TX; O. Ishizuka, Geological Survery of Japan, AIST, Tsukuba, JAPAN

1. Introduction The world's largest oceanic core complex, Godzilla Mullion, occurs along the extinct spreading center of the Parece Vela Basin (PVB) in the Philippine Sea. Based on poorly constrained magnetic data, spreading was thought to be intermediate (8.8–7.0 cm/y full-rate); ceasing at ~12 Ma. Although a higher magmatic budget is expected for a fast- to intermediate-spreading ridge, the PVB shows features indicating a smaller magmatic budget such as oceanic core complexes and abundant abyssal peridotites (Ohara et al., 2001; 2003). Godzilla Mullion consists of a huge corrugated detachment fault surface and what was called the "hanging wall massif". Next to this "massif", is a large alkaline axial

volcano that erupted at ~4.6 Ma (Ishizuka et al., 2004). Ishizuka et al. interpreted this volcano as "post-spreading": erupting several million years after cessation of spreading at ~12 Ma. 2. New observations 2-1. New age dating We have new radiometric ages by Ar-Ar on basalts and U-Pb on gabbroic rocks from Godzilla Mullion that indicate a significant decline and asymmetry in spreading rate for the terminal phase of PVB spreading. The new basalt ages indicate ~1.9 cm/y for unroofing of the core complex, and ~1.2 cm/y for spreading of the conjugate crust. 2-2. Secular variation in peridotite petrology The peridotite petrology indicates a secular variation at Godzilla Mullion. Those from its distal end (i.e., near the breakaway zone) are moderately depleted (spinel Cr# = 0.3-0.4), while those from the medial part are more fertile (spinel Cr# =0.14-0.22), and those from the proximal part (i.e., near the termination) show abundant evidence for melt impregnation, with plagioclase pseudomorphs and elevated TiO2 and spinel Cr#. The high abundance of plagioclase peridotites at the proximal part could be related to stagnation of melts in a thickened lithospheric upper mantle leading up to cessation of spreading. 2-3.
Important new sampling result In 2009 we recovered peridotites as well as basalts from what was called the "hanging wall massif". We interpret this to indicate that magmatism declined to the extent that Tucholke et al.'s (2008)'s lower limit for detachment formation was crossed, and a different rifting mechanism took over. 3. New scenario for Godzilla Mullion evolution The new age data indicate that the terminal phase of PVB spreading was not intermediate, with a significant decline and asymmetry accompanying formation of Godzilla Mullion. This should have had profound effects on the thermal structure of the lithosphere in the rift, including progressive lithospheric thickening, decreasing degree of partial melting, and increased melt stagnation. This is consistent with the peridotite recovery from what was called the "hanging wall massif", and may explain morphotectonics similar to that at ultraslow-spreading ridges. Based on this scenario, the 4.6 Ma axial alkaline volcano is not "post-spreading", but the final product of PVB spreading and magmatism at a terminal ultraslow phase.

Poster II-64

Emplacement of Plutonic Bodies in Oceanic Core Complexes

<u>Olive, Jean-Arthur L.</u>; Behn, Mark; Tucholke, Brian

E J.L. Olive, MIT/WHOI Joint Program, Cambridge, MA; M. Behn, B.E. Tucholke, Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA

We present new thermo-mechanical models for the development of oceanic core-complexes (OCCs) in which magma is emplaced in both the brittle lithosphere and ductile asthenosphere. The magmatic material is tracked throughout the formation and evolution of the OCC to quantify the partitioning of crustal emplacement in the footwall of the detachment, as well as on the conjugate side of the ridge axis. The rate of magma injection is defined by the ratio of the magmatic to the total extension, M, and set to different values above and below the brittle-ductile transition, M_B and M_D, respectively. This parameterization allows for the possibility that the intrusion and along-axis propagation of dikes may be decoupled from the emplacement of gabbroic bodies at depth. Similar to previous studies, we find that OCC formation requires M_B ~ 0.5, but is not sensitive to M_D, or to variations in M_D through time. Further, we show that all magma injected in the brittle layer is accreted on the side of the ridge axis opposite the OCC, while magma injected in the ductile layer is emplaced symmetrically in the OCC footwall and on the conjugate side of the ridge axis. We derive scaling relations to estimate the expected crustal thickness on both sides of the axis, as a function of M_B, M_D and total height of the magma injection zone. Based on these relations, we can expect gabbro bodies up to 3-4 km thick in OCC footwalls, consistent with recent seismic observations. Finally, we suggest that the decoupling of magma emplacement via along-axis propagation of dikes and the emplacement of gabbroic bodies at depth can explain the large discrepancies in size and continuity of plutonic bodies observed in OCCs, and account for OCC formation at elevated magma supply.

Oral – Sunday 9th, 11:45

Microbial Communities and Metabolisms From Basalt- and Ultramafic-hosted Vents

Perner, Mirjam; Seifert, Richard; Strauss, Harald; Petersen, Sven

Perner, M, Microbiology, Univ. of Hamburg, Hamburg, GERMANY; Seifert, R., Biogeochemistry and Marine Chemistry, Univ. of Hamburg, Hamburg, GERMANY; Strauss, H., Geology, Univ. Münster, Münster, GERMANY; Petersen, S., IFM-GEOMAR, Kiel, GERMANY

High-temperature vent fields along the Mid-Atlantic Ridge (MAR) are characterized by two different modes of hydrothermal circulation. In basalt-hosted systems fluids rise through gabbros or basaltic lavas, often over long distances along deep-reaching detachment structures. Similar detachments are likely responsible for the formation of hydrothermal fields several kilometres away from the neovolcanic zone in areas of mantle-derived rocks, where the fluids pass through the cooling ultramafic footwall. Consequently, fluid chemical signatures differ considerably according to the host rocks in the subseafloor. The effluents from basalt-hosted settings are generally enriched in sulfide, whereas ultramafic regimes discharge H_2 and CH_4 enriched fluids. The dilution of the high-temperature endmember solutions with oxygenated ambient seawater also contributes to vent fluid chemistry by admixing oxygen, nitrate and sulfate to the reduced emissions. The fluid-rock interactions and the mixing processes likely denote geochemical constraints on the diversity and activity of local microorganisms.

The hydrothermal fluids of the basalt-hosted vent fields at 5°S and 9°S (Lilliput hydrothermal field) along the MAR are hallmarked by comparatively low H_2 concentrations. In contrast, those of the ultramafic-hosted vent fields at 15°N (Logatchev hydrothermal field) and at 8°S (Nibelungen field) along the MAR are considerably enriched in H_2. Diffuse and hot hydrothermal effluents from two H_2-poor sites in the basalt-hosted southern MAR fields and from four H_2-rich localities within the ultramafic-hosted Logatchev field were used for comparing the diversity of H_2-oxidizing microbes. To asses the microbial metabolic activities, hydrothermal fluids from seven basalt-hosted vents at 5°S and 9°S and from three ultramafic-hosted sites in the Logatchev and the Nibelungen fields were spiked with H_2 or sulfide and supplemented with radioactively labeled inorganic carbon. The fluids were incubated at moderate temperatures and microbial hydrogen or sulfide consumption as well as CO_2 fixation rates determined.

The enzyme catalyzing the microbial consumption of H_2 is the hydrogenase and its encoding gene is found in phylogenetically diverse microbial lineages. Only few phylogenetically diverging hydrogenase genes were identified in the two H_2-poor effluents from the basalt-hosted sites and were associated with those of mesophiles only. On the contrary, a high hydrogenase diversity is illustrated in the four investigated H_2-rich Logatchev habitats. Here the hydrogenase genes are affiliated with those of distinct mesophilic and (hyper)thermophilic microbes, reflecting the broad thermal range at which microbial H_2-oxidation is putatively performed. The highest microbial H_2-consumption rates were exhibited from a basalt-hosted venting sample characterized by extremely low H_2 concentrations in the natural environment (<5 nM) and a very low hydrogenase diversity. In most of the ten fluid incubations H_2 could stimulate microbial CO_2 fixation, while only in one incubation CO_2 fixation could be significantly enhanced by spiking the fluids with sulfide. This indicates the importance of H_2 for stimulating microbial CO_2 fixation in H_2-poor as well as H_2-rich vent environments at moderate temperatures. The results also suggest that the availability of H_2 in the fluids is not the sole determinant for the diversity and activity of H_2-oxidizing microorganisms. Other parameters such as mixing processes influencing the oxygen availability and temperatures of the effluents likely contribute to the metabolic diversity and activity of H_2-oxidizing microorganisms in these vent regimes.

Poster II-73

Modes of Deformation in Ultramafic Rocks Exhumed in the Footwall of Detachment Faults at Slow-spreading Ridges and Ocean Continent Transitions

Picazo, Suzanne M.; Cannat, Mathilde; Manatschal, Gianreto; Delacour, Adélie;

Escartin, Javier; Silantiev, Sergei; Fouquet, Yves

S.M. Picazo, M. Cannat, J. Escartin, CNRS-IPGP, Paris, FRANCE; G. Manatschal, CNRS-IPGS, Strasbourg, FRANCE; A. Delacour, LDTPOMP, Université Paul Sabatier, Toulouse, FRANCE; S. Silantiev, Laboratory of Geochemistry of Igneous and Metamorphic Rocks, Institut of Russian Academy of Sciences, Moscow, RUSSIAN FEDERATION; Y. Fouquet, Géosciences Marines-Géochimie Métallogénie, Ifremer, Brest, FRANCE
Mantle exhumation by detachment faulting occurs both at mid-ocean ridges and in the distal parts of rifted continental margins in Ocean Continent Transition (OCT). In this poster, we present deformation structures in ultramafic rocks sampled in the footwall of detachments, within 100-200m of the main fault, in the 13°-15°N region of the Mid-Atlantic Ridge (MAR-13N), and in the fossil remnants of a Jurassic OCT in the Swiss Alps (Totalp and Tasna). Our MAR work is carried out on dredged samples and on samples recovered during ROV dives (Serpentine cruise; 2007). For each type of deformation, we use the number of affected samples relative to the total number of ultramafic samples in our collection (247 samples) as an indicator of the distributed character of this deformation.

Ductile shear zones with recrystallization of primary minerals (olivine, pyroxenes) are rare both in the Alps and in the MAR-13N collection (<2% of the samples). In both settings, these ductile shear zones are not clearly linked with the detachment faults. Brittle deformation with serpentine and carbonate-filled veins and occasional clast-supported cataclasites is widespread in the Alpine outcrops and its intensity increases toward the detachment. In the MAR-13N ultramafic samples, this brittle imprint is also present (50 samples or 20%). In addition, the MAR samples commonly (115 samples or 46,5%) display variably sheared amphibole and chlorite veins, with occasional apatite and zircon, which we interpret as hydrated magmatic veins. Chlorite, tremolite after primary hornblende, and less common talc grow during this deformation but are also locally kinked and fractured. The veins appear to form in brittle cracks in variably serpentinized peridotite host rock. Next to the veins, pre-existing serpentine is replaced by talc.

In a few MAR-13N samples (45 samples or 18%), we observe intense brittle-ductile deformation in tremolite-chlorite-serpentine schists, with occasional talc. These samples have seen large strains with coeval fluid circulation, and are similar to those described in the main detachment fault at other MAR locations (D'Orazio et al., EJM 2004, Boschi et al., Ofioliti 2006, Escartin et al., Gcubed 2008).

Finally matrix supported cataclasites are observed in rare (only 4) samples from the MAR-13N collection, but we have not observed gouges similar to those that form thin shear zones next to the detachment in the Alpine outcrops.

These results suggest that syntectonic magmatic injections and subsequent brittle-ductile shearing of their hydrous alteration products are a characteristic of detachment faulting leading to mantle exhumation in the MAR-13N region. By contrast, deformation observed near detachments in the Alpine fossil OCTs is primarily brittle and amagmatic.

Poster II-54

New Variscan 40Ar-39Ar Ages for the Danubian Ophiolite

Plissart, Gaëlle; Monnier, Christophe; Maruntiu, Marcel; Neubauer, Franz; Diot, Hervé

Plissart, G., Monnier, C., Diot, H., University of Nantes, Nantes, FRANCE; Plissart, G., University of Brussels, Brussels, BELGIUM; Maruntiu, M., IGR, Bucharest, ROMANIA; Neubauer, F., Dep. of Geog and Geol, Salzburg, AUSTRIA

The Danubian ophiolite consists of four dismembered massifs cropping out in the Southern Carpathians and the Balkans mountains and belonging to the Upper Danubian Alpin unit: Tisovita Iuti in Romania, Deli Jovan and Zaglavak in Serbia and Tcherni Vrah in Bulgaria. These four massifs would represent the relics of a unique oceanic domain delineating a 160 km-long tectonic suture dismembered by Oligocene Alpine tectonics. Although the age of this ophiolite has been considered as Late Proterozoic in age (Haydoutov 1989), the Deli Jovan massif has recently been dated to the Lower Devonian (U-Pb zircon age of 405 ± 2.6

Ma; Zakariadze et al., 2006). In this case, the Danubian ophiolite could be considered as a remarkable marker of a Variscan paleo-ocean according to its size (~ 500 km2) and its lithological diversity.

This study is focused on the transformation of gabbroic rocks, evidenced by a continuous petrographic sequence from the amphibolitized to listvenitized gabbros (zoisite + calcite + (Cr-) chlorite + (Cr-) muscovite assemblage). The geothermometry on chlorite from these metagabbros (Plissart et al., 2009) suggests a two-stage transformation: a common and large scale retrograde ocean-floor metamorphism in the transitional amphibolite/greenschist facies occurring at ~ 450°C, locally superimposed by a listvenitization process at ~ 280°C. This latter event suggests important geochemical remobilizations linked to seawaterderived fluid/rock interactions.

New 40Ar-39Ar ages have been performed on one hornblende from amphibolitized gabbros and two Crmicas from listvenites. The amphibole analyse gives a plateau age of 472.2 ± 3.2 Ma, whereas the Crmicas ones give plateau ages of 372.6 ± 1.3 Ma and 360.6 ± 1.2 Ma. These results are consistent with a Variscan age for the Danubian ophiolite and confirm the two-stage transformation of gabbros. Amphibolitization processes could be considered as a very early stage probably linked to normal faulting at the ridge, whereas listvenitization ones might be viewed as a late event. In this case, listvenitization processes could either be related to deformation and transformation occurring (1) within the accretionary wedge, (2) during an intra-oceanic obduction or (3) during a continental obduction. The first hypothesis seems more likely considering the large amount of water necessary to generate the listvenites and the widespread presence in the area of sedimentary thrust slices.

Haydoutov, I. (1989): Precambrian ophiolites, Cambrian island arc, and Variscan suture in the South Carpathian-Balkan region. – Geology, 17(10):905-908.

Plissart, G., Féménias, O., Maruntiu, M. Diot, H., Demaiffe,D. (2009): Mineralogy and geothermometry of gabbro-derived listvenites in the Tisovita Iuti ophiolite, Southwestern Romania. – The Canadian Mineralogist, 47:81-105.

Zakariadze, G.S., Bayanova, T.B. & Karpenko, S.F. (2006): Age, composition and origin of the paleooceanic gabbros of Deli Jovan Massif (NE Serbia). – Ofioliti, 31 (2): 223-224.

Poster I-14

A Continuous Structural Characterisation of Atlantis Massif Using an Integrated Analysis of Oriented Downhole Imagery and Logging Data

Pressling, Nicola; Morris, Antony; John, Barbara E; MacLeod, Christopher J.

N. Pressling, School of Ocean and Earth Science, University of Southampton, Southampton, UNITED KINGDOM; N. Pressling, A. Morris, School of Geography, Earth and Environmental Sciences, University of Plymouth, Plymouth, UNITED KINGDOM; B.E. John, Department of Geology and Geophysics, University of Wyoming, Laramie, WY; C.J. MacLeod, School of Earth and Ocean Sciences, Cardiff University, Cardiff, UNITED KINGDOM

Continuous wireline logging data are invaluable when less than 100% of drilled core material is recovered. The data provide information on missing units, record the true depth of features and uniquely constrain spatial orientation. Only by fully integrating continuous, oriented logging data and discrete, finer-scale core data can we develop a complete structural interpretation for drill holes that is not limited by sampling bias.

Integrated Ocean Drilling Program (IODP) Expedition 304/305 sampled the Atlantis Massif oceanic core complex at the intersection between the Mid-Atlantic Ridge and the Atlantis Transform fault at 30° N. Hole U1309D penetrated 1415.5m into the central dome of the massif, which exposes the corrugated detachment fault surface denuding the lower crust and upper mantle. The recovered section is dominated by gabbro compositions that are complexly faulted and layered on a variety of scales, reflecting the complicated interplay between magmatic and tectonic processes controlling the formation, evolution and deformation of oceanic crust at slow-spreading ridges.

The average core recovery at Atlantis Massif was 74%. Therefore, to augment and constrain structural interpretations based on limited core material, we used the Formation

MicroScanner (FMS) wireline logging tool that measures microresistivity contrasts in the immediate vicinity of the borehole wall formation. The data are presented as an unwrapped image of the borehole cylinder, and inclined planar structural features that intersect the borehole, such as faults or veins, are shown as darker (more conductive) sinusoidal traces. The true dip and azimuth of these features can be calculated directly due to the inclusion of an accelerometer and magnetometer on the toolstring, which record the position and spatial orientation (with respect to magnetic north) of the tool within the borehole, respectively.

4324 distinct structural features have been identified in the FMS images between 97 and 1415mbsf (metres below sea floor). Distinctly different structural trends are seen across the five sub-units that are based on petrological and geochemical observations of the recovered core. In addition, variations in the borehole dimensions are used to define 115 zones of borehole breakout, with a cumulative extent of 434.76m (31% of the total drilled). Such regions often correspond to areas of poor recovery and are consequently poorly characterised using core samples. The extensive FMS-based structural database allows the variation in fracture networks and areas of weakness to be quantified at a high-resolution, leading to improved understanding of the hydrothermal fluid flow and melt pathways in the footwall section.

Poster II-50

Detachment Faulting and the Formation of Oceanic Core Complexes

<u>Reston, Timothy J.</u>; Ranero, Cesar

T.J. Reston, Geography Earth and Environmental Sciences, Birmingham, UNITED KINGDOM; C. Ranero, Barcelona Center for Subsurface Imaging, Instituto de Ciencias del Mar, CSIC, Barcelona, SPAIN

The corrugated surface of oceanic core complexes (OCCs) are though to represent the slip surface of large-offset normal faults, commonly called detachment faults, that cut to depth beneath the median valley of the spreading centre. A detachment fault represents a normal fault that has remained active even as large offsets develop, resulting in the rotation of the exhuming footwall of the fault to relatively low-angles: the rolling hinge model. However there are two different types of rolling hinge model. The key difference is whether the angle at which slip along the fault is no longer possible occurs beneath or above top basement. If beneath top basement, the upper portion of the fault locks up, while the deeper root zone remains active, requiring that a new fault splays off the root zone, cutting at a steep angle through the hangingwall to the surface. In so doing, it transfers a slice of the hangingwall to the footwall; the slice is then rafted to the surface. Repetition of the process results in a series of stacked rafted blocks on a rotated, inactive series of fault segments, resembling a single detachment fault (we term a Rolling Hinge Type 1 or RH1 detachment) on which several fault blocks have moved. However none of these blocks will have moved at low angle, but only been passively rotated during the rafting process to low-angle. In the alternative rolling hinge model (RH2), the angle at which the fault locks up is not reached until the slip surface has been exhumed above top basement. This allows movement on the entire fault zone to continue, resulting ins the progressive unroofing of deep crustal and mantle rocks until such time as the fault is abandoned for other reasons. Such a RH2 system explains the formation of many oceanic core complexes that are observed. We see evidence for both types of rolling hinge detachment along the Mid-Atlantic Ridge. In some cases, such as the North Atlantis Inside Corner, it can be shown that a detachment fault that forms an exhumed oceanic core complex near the segment end continues towards the segment middle beneath an increasing number and thickness of small fault blocks. We suggest that this represent an along strike transition from a RH2 detachment at the segment end to a RH1 detachment further toward the segment middle. The transition between the two being related to the depth at which the fault rotates to its lock-up angle. The identification of an RH1 detachment here was however only possible because of its along strike transition to a RH2 detachment; elsewhere RH1 detachments may exist beneath a continuous layer of small rafted blocks and not be recognized from bathymetric data.

Poster I-36

Host-rock Composition Shapes the Microbial Community Structure Associated With Hydrothermal Vent Deposits

Reysenbach, Anna-Louise; Flores, Gilberto; Campbell, James; Kirshstein, Julie; Podar, Mircea; Steinberg, Josh; Voytek, Mary

A.L. Reysenbach, G. Flores, J. Steinberg, Biology, Portland State Univ, Portland, OR; J. Kirshstein, M. Voytek, USGS, Reston, VA; J. Campbell, M. Podar, Oak Ridge National Labs, Oak Ridge, TN

Newly formed deep-sea hydrothermal vent deposits are rapidly colonized by a range of autotrophic and heterotrophic thermophiles. The assembly and structure of these microbial communities are likely influenced by the different hydrothermal fluid chemistries generated at periodotite (ultramafic) and basalt (mafic) hosted vent fields. We explored the microbial phylogenetic diversity associated with deposits from Lucky Strike (mafic) and Rainbow (ultramafic) vent fields using high throughput pyrosequencing of 16S rRNA gene amplicons. Additionally we compared the distribution of sulfate reducers (using the functional gene dsr) and methanogens (using mcr as the diagnostic gene for this group) and show that using these different approaches, thermophilic methanogens are essentially absent at Lucky Strike. It is likely that the high concentrations of hydrogen at Rainbow can support a suite of hydrogen oxidizers including methanogens, whereas, because of the unusual hydrothermal vent chemistry, and in particular the very low hydrogen concentrations at Lucky Strike, the hydrogen is below the threshold concentration that would support methanogen growth. These results continue to expand our understanding on the tight coupling between geochemistry and biology in the deep-sea.

Oral – Friday 14th, 15:15

The Microbiology of OCC's: Implications for Life in the Subsurface and Elsewhere in the Solar System

Reysenbach, Anna-Louise

Portland State University, Biology Department, Portland, OR 97201, USA

Oceanic core complexes provide long-lived, high and low temperature, hydrothermal circulation, rich in hydrogen. These systems support a unique microflora whose diversity is tightly coupled to the geochemistry of the hydrothermal fluids. Comparisons with mafic- and ultramafic- hosted systems have revealed the prevalence of methanogens and other hydrogen-oxidizing chemolithotrophs at ultramafic sites like Rainbow and Logachev. High throughput DNA sequencing approaches have provided clues into the patterns of diversity associated with these systems, and point to a much greater diversity of novel microorganisms from deep-sea vents. In addition, although some of the metabolisms may be similar, each vent field has its very unique microbial signature. Interestingly, the microbial diversity detected at Lucky Strike points to the hypothesized subsurface biosphere below the lava lake, as no methanogens were detected, yet elevated methane is measure in these vent fluids. Studies of hydrothermal systems have implications for our understanding of what fuels the microbial subsurface biosphere and the extent of the microbial world on Earth and elsewhere in the solar system.

Poster II-70

Detachment Faulting Chronology in Oceanic Crust Using Radiometric Dating of Associated Hydrothermal Deposits: TAG Hydrothermal Field, Mid-Atlantic Ridge 26○N

Rona, Peter

IMCS, Rutgers University, New Brunswick, NJ

Hydrothermal systems at ocean ridges involve seawater (ubiquitous), heat sources (magma, mantle upwelling, mining heat from crust. exothermic mineral reactions), rocks of ocean crust and upper mantle, and permeable pathways through these rocks for convective circulation of the heated seawater. Detachment faulting can provide pathways for the hydrothermal circulation. Limited evidence including heat budgets and dating of hydrothermal precipitates indicate that hydrothermal systems at ocean ridges are episodic with relatively short on and long off intervals. The inferred episodicity is influenced by the rate of extraction versus replenishment of heat and sealing of circulation pathways by hydrothermal precipitation. The observation that ancient and modern volcanogenic massive sulfide (VMS) deposits tend to occur at the intersection of fault systems and the rapidity of self-sealing by hydrothermal precipitation suggest that faulting is a primary control of episodicity where adequate heat sources exist. Manganese crusts and massive sulfides are precipitated from low- and high-temperature solutions, respectively, in seafloor hydrothermal fields. The distribution and chronology of these precipitates in a hydrothermal field on an ocean ridge record of the distribution and state of the faulting that provided the pathways for the associated hydrothermal circulation. The TAG hydrothermal field near 26oN on Mid-Atlantic Ridge provides a setting to test relations between hydrothermal precipitates and the development of faulting in space and time. At least four large (diameter hundreds of m; height tens of m) massive sulfide mounds ranging in state from young-hot to old cold and in age up to over 100,00 years, as well as manganese crusts, are distributes in a 5 by 5 km area of the hanging wall of an inferred detachment fault zone involving the east wall of the axial valley. Radiometric dating of seafloor deposits from the mounds and sub-seafloor deposits recovered from the young-hot sulfide mound by ODP Leg 158 drilling indicate that the mound has undergone relatively short intervals of high-temperature activity (hundreds of years) and longer intervening inactive intervals (thousands of years) for the past 50,000 years. A field-wide high-temperature hydrothermal event affected all four sulfide mounds about 50,000 years ago. This chronology and distribution of hydrothermal precipitates may record the development and state of the detachment fault zone which provided the pathways for the hydrothermal circulation that produced the mineralization . Our TAG team has proposed to the IODP a second leg to extend the drilling/logging to sample the whole sequence of mounds in order to address gaps in the chronologic record of hydrothermal activity and to use this information to elucidate the development of the detachment fault zone.

Poster II-67

H2 Production From Ultramafic-Bearing Rock Assemblages: An Experimental Study at 420°C, 500 bars

<u>Rough, Mikaella E.</u>; Seyfried, William E.

Geology and Geophysics, University of Minnesota, Minneapolis, MN

Black smoker fluid issuing from Pacific ocean vent sites illustrate the predictably close linkage between the chemistry and temperature of vent fluids and the sub-seafloor magma chambers that underlie these systems at shallow depths. Yet hydrothermal venting at slow-spreading systems in the Atlantic periodically reveal an association with ultramafic-bearing lithologies and coexisting detachment faulting that contains hard to constrain chemistry and temperature conditions. Systems like Rainbow reveal low pH fluids with temperatures measured at the seafloor >360°C, high integrated rates of flow, high concentrations of methane and other dissolved organics, dissolved H2 concentrations 1-2 orders of magnitude higher than typical of basaltic hydrothermal systems, and high dissolved transition metal concentrations.

The complex nature of the vent fluids cannot be explained by reacting seawater with pure basalt or pure ultramafic rock at vent exit temperatures, indicating that a more complex rock-matrix and reaction model must be used to explain slow-spreading hydrothermal vent systems. Drill core samples obtained from uplifted lower crust-upper mantle fault zones indicate that gabbros frequently intrude into more olivine rich rocks producing rock compositions like troctolite and olivine-rich (70% olivine) troctolite.

We conducted an experiment on plagioclase-rich troctolite rock powder (80-150μm) at 420°C, 500 bars with a 0.8 mol/kg NaCl fluid to observe the evolution of saline solutions in contact with troctolitic rocks in the sub-surface reaction zone. The experiment yielded Al and H2 levels higher than Rainbow, similar Si concentrations, and Ca, Fe, K, and Li levels that were much lower than Rainbow vent fluid concentrations.

The quantity of H2 produced was previously attributed to the dissolution of fayalitic olivine and resulting precipitation of magnetite at temperatures below 400°C, yet the rock powder used in this experiment was dominated by plagioclase and contained less olivine than previously conducted experiments using powdered-olivine-rich rock assemblages (Allen, 2003). Seyfried et al. (2008) illustrated that an experiment with only silica and olivine does not react to completion as predicted; instead it limits the reactivity of the minerals. Therefore, the large quantities of H2 produced in the troctolite experiment indicate that large H2 concentrations result from the reaction of olivine in an Al-bearing system at all temperatures. This concludes that the fluid production in ultramafic-bearing environments necessitates a more complex rock matrix, and can result from the hydration of fayalitic-olivine at temperatures above 400°C.

Poster I-31

Interplay Between Tectonic and Magmatic Events During the Exhumation of a Gabbro-peridotite Section to the Sea-floor (Northern Apennine ophiolites, Italy)

Sanfilippo, Alessio; Tribuzio, Riccardo

A. Sanfilippo, R. Tribuzio, Dipartimento di Scienze della Terra, Università di Pavia, Pavia, Pavia, ITALY; R. Tribuzio, C.N.R. - Istituto di Geoscienze e Georisorse, Unità di Pavia, Pavia, Pavia, ITALY

The Scogna-Rocchetta Vara ophiolite from Northern Apennine is a Middle-Upper-Jurassic sequence made up of mantle peridotites intruded by different gabbroic bodies and topped by a sedimentary cover mostly made of gabbroic breccias and radiolarian cherts. This ophiolite thus lacks the basalt layer, similar to the "magma-starved sections" from the Mid-Atlantic Ridge (e.g. at 14°-16° N). The mantle peridotites are clinopyroxene-poor depleted lherzolites affected by a spinel facies deformation that produced a foliation sub-perpendicular to the stratification of sedimentary cover. The lherzolites locally contain thin pyroxenite levels, attributed to infiltration of MORB-type melts under spinel facies conditions. Plagioclase-orthopyroxene veinlets, associated with minor clinopyroxene, are frequent in the lherzolites and parallel to the spinel facies foliation. These veinlets document that decompression of the mantle section to plagioclase facies conditions was associated with melt impregnation by silica-oversatured melts. The lherzolite stuctures are replaced by dunite bodies containing spinel trails that are nearly parallel to the plagioclase-orthopyroxene veinlets. Spinel from the dunites have low Cr#, similar to spinel from replacive dunites of (ultra-)slow spreading ridges. The peridotites are crosscut by two generations of gabbroic bodies, which both retain a MORB-type geochemical signature. The first generation is represented by gabbroic dykes (troctolites to clinopyroxene-rich gabbros) that are concordant with the mantle structures and display diffuse contacts to the host rock. The dykes are post-dated by clinopyroxene-rich gabbro sills showing sharp contacts with the host lherzolites, which are elongated nearly parallel to the stratification of sedimentary cover. The gabbroic sills are most likely associated with the development of a large gabbroic intrusion that mostly consist of coarse grained olivine-bearing gabbros and minor foliated troctolites. The gabbroic intrusion contains up to 50 m thick lenses of mantle lherzolite remnants and up to 80 m thick bodies made up of olivine-rich troctolites locally intruded by gabbroic sills. The olivine-rich troctolites are texturally and compositionally similar to those from oceanic core complexes from Mid Atlantic Ridge and document a process of infiltration of MORB-type melts into an olivine-rich matrix. The gabbroic intrusion shows sparse ductile shear zones that are nearby parallel to the basement-sediment contact. The ductile evolution comprises early re-crystallisation of clinopyroxene and plagioclase (± Ti-pargasite) at T ~850 °C, followed by an amphibolite facies event characterised by hornblende and plagioclase at T ~700 °C. The subsequent brittle evolution was initially associated with injection of MORB-type basalt dykes. The following exhumation of the gabbro-peridotite sequence to the sea-floor is correlated with calcite- and hematite-bearing structures in both gabbros and mantle-derived serpentinites.

Poster I-23

The Magnetic Signature of Non-volcanic Domains on the Southwest Indian Ridge Between 61E and 67E

Sauter, Daniel; Cannat, Mathilde; Mendel, Véronique

D. Sauter, V. Mendel, Institut de Physique du Globe de Strasbourg, CNRS-UMR 7516, University of Strasbourg, Strasbourg, FRANCE; M. Cannat, Equipe de Géosciences Marines, CNRS-UMR7154, Institut de Physique du Globe, Paris, FRANCE

We investigate the magnetic signature of non-volcanic seafloor areas along the Southwest Indian Ridge between 61E and 67E and analyze their relationship with crustal thickness variations and past to present ridge segmentation. This part of the Southwest Indian Ridge is an end-member for the global ridge system in terms of low melt supply, thin crust, and ultraslow-spreading rates. It is characterized by large expanses of smooth seafloor that show no evidence for a volcanic upper crustal layer. Off-axis, the amplitudes of magnetic anomalies C5n and C6n are on average higher over volcanic seafloor areas where thicker crust is inferred (low residual Mantle Bouguer Anomalies RMBA values) and lower over smooth non-volcanic seafloor with inferred thinner crust (high RMBA values). Local standard deviation of the magnetization, a proxy for magnetization contrast, is on average higher for volcanic seafloor than for smooth non-volcanic topography suggesting that the contribution of the basaltic upper crustal layer to the production of magnetic anomalies remains important in off-axis regions. However, the distribution of crustal magnetization in volcanic seafloor and smooth seafloor domains overlap broadly, and smooth seafloor or corrugated domains generally show reasonably good records of the geomagnetic polarity history. Furthermore, along isochron variations of crustal magnetization show that smooth seafloor domains locally have higher crustal magnetization values over thick crust areas than volcanic seafloor domains. This indicates that basalts are not the only source of the magnetic anomaly record in our study area. The lithologies in smooth seafloor area are inferred from the small number of available dredges to be mostly serpentinized peridotites. Gabbros and diabase samples are very scarce in these dredges. Gabbros may, however, be present in smooth seafloor areas that have not been sampled so far. Although the variations of the thickness and the intrinsic magnetization of gabbros are not well constrained, we infer from tentative two-dimensional forward models that an alternative source, besides gabbros, is needed to explain the magnetic signal of smooth non-volcanic seafloor areas. An induced component of magnetization is present locally in some high RMBA smooth seafloor areas, but it is not systematic and it is weak over most parts of the survey area. Serpentinized peridotites are likely carriers of this induced magnetization component. We propose that both gabbros and serpentinized peridotites may contribute to the variable amplitude of magnetic anomalies measured over smooth non-volcanic seafloor. This work has been partially published in Sauter D., Cannat M. and Mendel V., 2008, Magnetization of 0-26.5 Ma seafloor at the ultraslow spreading Southwest Indian Ridge 61-67°E. Geochem. Geophys. Geosyst., 9, Q04023, doi:10.1029/2007GC001764.

Poster I-34

Aspects of Mantle Exhumation During Magma Starved Rifting at the Galicia Margin

Sawyer, Dale; Lasseigne, Amy

Earth Science, Rice University, Houston, TX

Recently, we have interpreted seismic profiles crossing the west and south sides of the Galicia Bank, west of Spain in the Atlantic Ocean, to suggest a heretofore unrecognized role of very large mass wasting events presumed to have occurred late in the process of continental breakup and the initiation of seafloor spreading. These events could have been driven by large topographic relief created at the boundary between the half-thickness, extended, continental crust of the Galicia Bank and crust composed of mantle rocks exhumed to the seafloor (Zone of exhumed continental mantle; ZECM) after the continental crust has separated and before normal seafloor spreading is established. The slide material is interpreted to consist of blocks of Galicia Bank extended continental crust and pre-sliding sediment. A portion of this slide material may have been emplaced over the ZECM. We examine possible consequences of this controversial hypothesis for the well-known and widely interpreted drilling and seismic data from the Galicia Bank Basin and Iberia Abyssal Plain.

The widely accepted model for magma-starved rifting and the initiation of seafloor spreading in this region posits that the prominent S reflector corresponds to a low angle detachment fault forming the base of the extended continental crust, overlies serpentinized upper mantle rocks and is the fault which exhumes continental mantle at the final stage of breakup. In the large mass-wasting model, the S reflector corresponds to the surface of separation of a slump, deposited upon already exhumed continental mantle. In either model, mantle exhumation associated with the separation of continental crust is an essential feature. In either case, the rifting processes at this margin show similarities to the processes of slow spreading rate ocean crust formation.

We have applied pre-stack depth migration to a number of additional 2D MCS profiles in this area. They include both dip and strike profiles, offering more three-dimensional insight into the rifting and exhumation process. The new images suggest more lateral complexity in the S-reflector than has previously been noted. Abrupt lateral changes in reflectivity in S seem to correspond to places where dipping reflectors in the mantle intersect S. We interpret these to be mantle faults offsetting S that formed before or during the final stage of continental separation. The places where mantle faults intersect S also seem to correspond to the along strike boundaries of the pod shaped fault bounded blocks in the overlying crust. It is not yet clear to us whether this is because they formed simultaneously or the presence of one controlled the formation of the other.

Poster II-49

Cooling History of the Atlantis Massif and Kane Oceanic Core Complexes at the Slow-spreading Mid-Atlantic Ridge

Schoolmeesters, Nicole; Cheadle, Michael J.; John, Barbara E.; Grimes, Craig B.

N. Schoolmeesters, M.J. Cheadle, B.E. John, Geology and Geophysics, University of Wyoming, Laramie, WY; C.B. Grimes, Geosciences, Mississippi State University, Mississippi City, MS

Understanding the cooling history of the lower crust exposed in oceanic core complexes helps establish denudation rates, the depth of gabbro emplacement, and subsequent hydrothermal circulation. Here we use newly acquired thermochronometic data to constrain the crystallization history of gabbros hosted in the footwalls of the Atlantis Masssif core complex at 30°N (IODP Hole 1309D), and the Kane oceanic core complex at 23°N, on the Mid-Atlantic Ridge. Combined U-Pb zircon crystallization ages taken with (U-Th)/He zircon ages allow determination of the cooling history of rocks sampled from these core complexes. The closure temperature for U-Pb in zircon from oceanic gabbros ranges between ~900-700°C, and the closure of the (U-Th)/He system for zircon is ~200°C in these rapidly cooled rocks. Intermediate temperatures can be potentially constrained by either multi-component remanent magnetization (300-550°C) and/or U-Pb ages in sphene (700-550°C). Thus thermochronometry can constrain the detailed cooling history from ~900°C to 200°C (John et al., 2004). We have determined (U-Th)/He ages for 6 samples from depths ranging between 40 and 1040 mbsf in IODP Hole 1309D, which together with U-Pb zircon ages constrain the cooling rate of gabbros emplaced into the center of Atlantis Massif. These cooling rates will be compared to those determined by Grimes et al. (2008) for samples from the south wall of Atlantis Massif, adjacent to the Atlantis transform. Downhole variation in (U-Th)/He age, taken with the present day geothermal gradient constrained by the bottom hole temperature of 120-140°C, also limits the orientation of the ~200oC isotherm as the core complex was denuded. These data may also place constraints on the depth of hydrothermal circulation beneath the detachment fault. At the Kane oceanic core complex, we will examine the lateral, along strike, variation in cooling rate and cooling history from the center to the edge of the core complex near the transform valley wall. These cooling rates must reflect the unroofing history of the core complex. Assuming the detachment fault that bounds the core complex slipped at a similar rate along strike of the ridge segment, any lateral variation in cooling rates will likely reflect variation in depth of the 700-900°C isotherms and hence constrain along strike variation in the depth of faulting and/or depth of gabbro emplacement. Gabbros near the transform fault likely crystallized at a deeper depth due to being near that cooler transform boundary, whereas gabbros at the ridge segment center likely crystallized at a shallower depth, consistent with the 600-700 kyr older U-Pb zircon ages from samples near to the transform fault.

Poster II-65

Tectonic vs Magmatic Extension in the Presence of Core Complexes at Slow-spreading Ridges From a Visualization of Faulted Seafloor Topography

Schouten, Hans; Smith, Deborah; Cann, Johnson R; Escartin, Javier

H. Schouten, D. Smith, Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA;

J.R. Cann, School of Earth and Environment, University of Leeds, Leeds, UNITED KINGDOM; J. Escartin, Groupe de Geosciences Marines, CNRS - IPGP, Paris, FRANCE

We develop a forward model of the generation of faulted seafloor topography (visualization) to estimate the relative roles of tectonic and magmatic extension in the presence of core complexes at slow-spreading ridges. The visualization assumes flexural rotation of 60° normal faults, a constant effective elastic thickness of young lithosphere, Te, and a continuous infill of the depressed hanging wall by lava flowing from the spreading axis. We obtain a new estimate of Te = 0.5 - 1 km from the shapes of the toes of 6 well-documented oceanic core complexes. We model an 80-km-long bathymetric profile in the Equatorial Atlantic across a core complex and the ridge axis at 13°20'N and estimate the variation in tectonic extension, which yields the variation in the fraction of upper crust extension by magmatic diking at the ridge axis, M. Core complex formation appears to be stable for all values of M < 0.5. The visualization shows how gabbro emplaced at the base of the lithosphere during extension by magmatic diking is partitioned to each side of the spreading axis, and predicts a high probability of finding gabbros in the domes of core complexes that correlates with M. From the bathymetry of the Kane Megamullion and of the conjugate sea floor east of the axis we estimate M in a similar manner and compare its variation with the lithology and geophysics of this oceanic core complex.

Poster I-10

Footwall Lithology Controls on Strain Localization Mechanisms and the Geometry of Oceanic Detachment Faults

Schroeder, Timothy J.; Cheadle, Michael J.; John, Barbara E.

T.J. Schroeder, Division of Natural Science and Mathematics, Bennington College, Bennington, VT; M.J. Cheadle, B.E. John, Geology and Geophysics Dept., University of Wyoming, Laramie, WY

Oceanic detachment faults serve locally as plate boundaries to accommodate plate separation and tectonically denude gabbro and mantle peridotite to the seafloor during magma-reduced spreading. Drilling and submersible sampling suggest that oceanic detachment faults form different patterns of seafloor morphology and employ different strain localization mechanisms depending on whether their footwalls are dominated by gabbro or mantle periodotite. Three ODP/IODP drill sites at detachment faults displaying classic corrugated domal “core complex” morphology, 735 (Atlantis Bank), 1275 (15°20′ Fracture Zone), and U1309 (Atlantis Massif), contain dominantly gabbro in their footwalls. Five ODP drill sites (1268, 1270, 1271, 1272 & 1274) north and south of the 15°20′ Fracture Zone Mid-Atlantic Ridge offset have footwalls comprising dominantly mantle peridotite with small (<50 m wide) gabbro intrusions. These faults form bathymetric ridges ~ 15-40 km long (parallel to the spreading axis) with ~2000 m of vertical relief and 10-15 km-wide flanks instead of the classic core complex morphology. The fact that these ridges have narrower flanks than core complexes suggests that these faults are shorter-lived and undergo less displacement than core complex detachment faults. Both types of detachment faults are present in the large area of magma-reduced spreading to the north and south of the 15°20′ Fracture Zone, but only 3% of the seafloor has the core-complex morphology. This suggests that core-complex style detachment faults represent a special case of oceanic detachment faulting, in which a greater proportion of plate separation is accommodated by magma intrusion than is the case for the ridge-like detachment faults.

High-temperature strain localization at both types of detachment faults is correlated with intrusions of melt or magma-derived fluids. At the Atlantis Bank and the Atlantis Massif core complexes, plastic strain is at least locally concentrated into horizons of Fe-Ti oxide gabbro that may have formed by infiltration of highly-evolved magmatic segregations. Strain localization may be the result of the rheologic contrast between low-ductile-strength Fe-Ti oxides and comparatively stronger silicates. The minimum temperature of penetrative deformation in these mylonites is estimated to be between 350°C and 700°C by two-oxide geothermometry of undeformed ilmenite-magnetite exsolution lamellae; indicating that brittle strain during final denudation was partitioned away from the oxide-gabbros. Strain localization at several peridotite-footwall, non-core-complex detachment faults ridge appears to have occurred within small intrusions of either oxide gabbro or plagiogranite. Tectonic mixing and chemical reaction between the magmas and host peridotite formed amphibole-chlorite schists and cataclasites. Strain appears to have remained localized into these schists until final footwall denudation based on the presence of overprinting low-temperature metamorphic assemblages and discontinuous deformation textures.

Poster II-57

Life Cycle of Oceanic Core Complexes, 1: Overview

Searle, Roger; MacLeod, Christopher J.; Murton, Bramley; Casey, John F.; Mallows, Chris; Harris, Michelle

R. Searle, C. Mallows, Earth Sciences, Durham University, Durham, UNITED KINGDOM; C.J. MacLeod, School of Earth & Ocean Sciences, Cardiff University, Cardiff, UNITED KINGDOM; B. Murton, M. Harris, National Oceanography Centre, Southampton, UNITED KINGDOM; J.F. Casey, University of Houston, Houston, TX

Results from a near-bottom geophysical and sampling study of the Mid-Atlantic Ridge at 13°N – 14°N identify the critical controls on oceanic core complex development and evolution, and increase our knowledge of their internal structure. We demonstrate how spatial (~1–10km) and temporal (~100ka–1Ma) variations in magma flux to the ridge axis directly control the formation, extent and duration of "tectonic spreading" at the Mid-Atlantic Ridge. OCC detachment faults initiate as high-angle (~65°) normal faults no different from surrounding valley-wall faults and, like them, rapidly flatten to dips of ~30° in response to flexural unloading. However, on some faults displacement persists for 1-2 Ma rather than being transferred inward to a new fault. This leads to enhanced footwall uplift, flattening of the fault to horizontal or beyond, and thus creation of a detachment. This long-term persistent slip is associated with local waning of the ridge-axis magma supply. It is aided by strain localisation and fault weakening resulting from seawater penetration and talc formation along the fault zones. We propose this is easier where crust is thin or heterogeneous with peridotite occurring at shallow levels. Our data show that ridge-axis volcanism is suppressed and locally absent when core complexes are active. Thus the majority of plate separation is accommodated by tectonic slip on a single detachment, rather than magmatic accretion. This results in highly asymmetric seafloor spreading. Effectively, at initiation of the detachment the plate boundary jumps from the ridge axis to the detachment fault then, as a consequence of asymmetric spreading, gradually migrates back toward the ridge axis. Detachment faults are terminated by the emplacement of renewed magma into their footwalls, either from below or, as we demonstrate at MAR 13°N, by propagation of neovolcanic ridges laterally across them from adjacent magmatically robust segments. We demonstrate clear differences in internal structure of OCC footwalls, including a smooth dome that we interpret as extruded mantle and a rough, strongly faulted massif that we interpret as mafic crust.

Poster II-61

Life Cycle of Oceanic Core Complexes, 5: Internal Structures and Comparisons

Searle, Roger

Durham University, Durham, UNITED KINGDOM

I have completed geophysical studies, including high-resolution sonar imaging, of oceanic core complexes in two areas: the Mid-Atlantic Ridge at 13°-14°N, and the South West Indian Ridge at 64°E. The sonar images provide unprecedentedly detailed views of the 2Ma-old FUJI Dome OCC (SWIR), and two active OCCs (MAR). The surface morphology is particularly clear in the young, actively slipping OCC at MAR 13°18′N. The part proximal to the spreading axis displays a smooth, striated dome that we interpret as extruded mantle, while the more distal part, which we interpret as the mafic crust is rougher, strongly deformed and faulted. If this interpretation is correct, the 13°18′N OCC thus presents an outstanding exposure of a complete crustal and upper mantle section. Having identified these features on the active OCC, I can recognise them, though not necessarily all together, in other OCCs, both in sidescan and in bathymetric images. Bathymetry from the SWIR also shows previously unreported topographic features similar to those reported by Smith & Cann (2006) at MAR 13°-14°N, including large complex massifs that may be linked OCCs, and a comparison of these will be given.

Poster II-78

An Antithetic Tilt of the Plutonic and the Sheeted Dikes Sections Evidenced by a Paleomagnetic Study Near the Village of Agros, Cyprus

Shaar, Ron; Ron, Hagai; Agnon, Amotz; Abelson, Meir; Ebert, Yael

R. Shaar, H. Ron, A. Agnon, Y. Ebert, The Institute of Earth Sciences, The Hebrew University, Jerusalem, ISRAEL; M. Abelson, Geological Survey of Israel, Jerusalem, ISRAEL

The exposure of the plutonic and the sheeted dikes sections in the area of the village of Agros allows a unique opportunity for a three-dimensional independent paleomagnetic versus structural reconstruction of the plutonic - sheeted dike interface. Here we report a paleomagnetic study aiming at quantitative reconstruction of decoupled rotation of the two sections. Following a structural mapping of Agar and Klitgord (1995), we sampled 15 paleomagnetic sites in the plutonic and the dikes sections along the two sides of a detaching "crush-zone". Six to eight field-drilled oriented cores were collected at each site and structural attitude were carefully determined. Alternating field (AF) and thermal demagnetization were used to isolate the characteristic remanent paleomagnetic vectors. The behavior in the demagnetization experiments suggests that characteristic magnetization in both sections is carried by fine-grained magnetite, whereas sometimes, a secondary component carried by iron-sulfides overprints the signal. The mean paleomagnetic vector of the sheeted-dikes shows a declination of 321°, an inclination of 64°, and $\alpha 95$ of 9° for 5 sites. The mean paleomagnetic vector of the plutonic section shows a declination of 289°, an inclination of 6°, and $\alpha 95$ of 6° for 9 sites. The paleomagnetic vector analysis clearly demonstrates a rotational partitioning of two independent domains separated by the "crushed zone". In order to quantify the amount of rotation for each domain with respect to the initial state in the axial zone, we test the hypothesis that the dikes were initially vertical at formation within the spreading axis, where they had acquired magnetic remanence. Since dikes appear in both of the domains, we rotated the paleomagetic vector of each dike according to the present structural attitude. A tilt corrected average vector yields declination of 308°, inclination of 30°, and $\alpha 95$ of 12°. Thus, the tilt correction may provide the initial state before the antithetic tilt initiated. Furthermore, the tilt corrected inclination is very close to the mean paleomagnetic vector of Troodos (TMV, 274/36° $\alpha 95$ =12.3°), supporting this approach. All together, the results suggest a composite rotation that can be described synthetically as two events: an antithetic tilt of ~60° about a horizontal axis, and a clockwise rotation about a vertical axis of ~35°.

Oral – Tuesday 11th, 11:00

Geophysical Constraints on the Structure of Detachment Faults: Stone Cole Facts, Red Hot Topics, and Everything In-between

Sohn, Robert

Woods Hole Oceanographic Institution, Woods Hole, MA 02543

Geophysical measurements provide unique constraints on the sub-surface structure of detachment faults, with the primary advantage being the ability to image active systems *in situ*. Whereas geological and geochemical studies of exhumed samples constitute a kind of post-mortem on 'dead' core complexes, geophysical techniques are capable of imaging and observing 'living' detachment faults. The combination of passive microearthquake data and active-source seismic refraction/reflection data, along with potential field gravity and magnetics data, have demonstrated that detachment faults, both oceanic and continental, are fundamentally different geological structures compared to 'conventional' extensional systems. In particular, detachment faults roll over from steep (70-80°) dips at depth in the lithosphere to shallow (20-30°) dips in the shallow crust, and they have arcuate epicenter patterns indicative of dome-shaped fault surfaces. In addition, the detachment footwall is composed of lower-crustal and upper mantle rocks that slip against an essentially stationary hanging wall, which is typically composed of highly-tectonized volcanics – at least in oceanic systems where primary lithologies are preserved. These basic characteristics are supported by numerical models, and as more data become available, it is striking how similar this basic structure is for both continental and oceanic systems, despite significant variations in geologic setting.

If geophysical methods enjoy the advantage of working on living patients, then so to do they suffer the drawbacks. The images may be equivocal, and the patient may present conflicting symptoms, which can preclude an unambiguous diagnosis. Moreover, despite the obvious similarities, it is nevertheless true that every detachment system has its own unique quirks that confound the urge to generalize. Finally, the number of active detachment faults that have been rigorously studied remains unacceptably low, particularly in the ocean, where the simplest and easiest to understand systems are to be found. For all these reasons there remain significant gaps in our understanding, and at the most fundamental level we do not understand the mechanics of crustal accretion and extension on dome-shaped detachment faults. The dome shape presents a space accommodation issue, and the nature of crustal deformation at the intersection of a detachment fault with normative ridge-parallel fault systems is anybody's guess. Although low-angle detachment faults are ubiquitous in the geologic record there are but a few observations of earthquakes on shallow dipping planes. Seismic images of core complexes typically reveal large domains of mantle lithologies, but efforts to drill these features have invariably result in the recovery of gabbro. Are these apparent discrepancies simply endemic features of low-angle faults and core complexes, or are they threads of evidence that threaten to unravel the whole paradigm?

Poster I-22

The Magnetism of Oceanic Core Complexes – the Kane OCC

Tivey, Maurice; Williams, Clare M.

Tivey, Woods Hole Oceanographic Institution, Woods Hole, MA; C. Williams, BP Exploration, Sunbury-on-Thames, UNITED KINGDOM

Marine magnetic anomalies can provide important insight into the structure, history, and lithologic composition of oceanic core complexes (OCCs) while paleomagnetic measurements can constrain crustal rotation and the timing of fault motion as well as the source and provenance of crustal magnetic properties. Detailed magnetic measurements of OCCs both in terms of anomaly measurements and rock magnetic results from surface sampling and drilling show a wide range of behavior leading to a somewhat complex picture of OCC crustal magnetization. For example, magnetic anomaly polarity reversals can either continue uninterrupted across some OCCs (e.g. Kane or Atlantis Bank 735B) or are severely disrupted in terms of coherency and anomaly amplitude (e.g. Mid Atlantic Ridge 12-14N or TAG). Similarly, paleomagnetic results reveal univectoral distribution in some drilled sections (Atlantis Bank, 735B) or show a complex directional history (e.g. MARK area). The Kane OCC on the southern side of Kane Transform Fault exposes both gabbro and serpentinized peridotites and also records an uninterrupted magnetic polarity boundary (C2r.2r/ C2An.1n, ~2.581 Ma). The Kane OCC thus provides a superb opportunity to investigate the relationship between crustal magnetization, its initial formation and subsequent evolution as part of a detachment fault system. Rock magnetic measurements from Kane OCC samples collected by ROV show that both the outcropping gabbro (NRM 1.5 A/m) and serpentinized peridotite (NRM 4.7 A/m) have sufficient magnetization intensity and stability to act as the source of the magnetization as well as an ability to record a coherent magnetic signal. Similarly, two transform parallel, near-bottom magnetic profiles acquired across the northern and central domes of Kane OCC using the autonomous vehicle ABE document the seafloor location of the reversal boundary. We used an Analytic Signal approach to extract information from these magnetic anomalies to determine the range of dip angle solutions for the reversal boundary, assuming an initial remanence direction parallel to the geocentric axial dipole. Curiously, the polarity boundary is determined to dip away from the spreading axis (134 deg. ±14 deg.) in the northern gabbro-dominated dome but towards the spreading axis (41 deg. ±17 deg.) in the serpentinized peridotite-dominated central dome. The polarity boundary in the northern region is interpreted to be a rotated cooling isotherm in a predominantly gabbroic layer. Two-dimensional modeling of core complex thermal structure indicates that a 580C Curie cooling isotherm with an initial dip of ~165 deg. at the ridge axis can be rotated by up to 45 degrees, to a maximum dip of ~120 deg. after 3 Ma. In contrast, the polarity boundary in the serpentinized peridotites along the central region likely reflects an alteration front. Assuming that the serpentinized peridotites experienced the same tectonic rotation as the northern gabbros, the initial dip of the polarity boundary near the ridge axis would be close to vertical (~76 deg.). This boundary geometry may result from perturbed isotherms that dip steeply towards the ridge axis in the footwall of the detachment fault due to seawater penetration.

Poster I-24

The Origin of the Smooth Zone in Early Cretaceous North Atlantic Magnetic Anomalies

Tominaga, Masako; Sager, William

W M. Tominaga, Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA; M. Tominaga, W.W. Sager, Oceanography, Texas A&M University, College Station, TX

Late Jurassic-Early Cretaceous marine magnetic anomalies observed in the North Atlantic exhibit an abrupt change in character in M5-M15 (130-140 Ma) crust. The anomalies are smoother with low amplitudes, and are difficult to correlate among nearby profiles. Previous studies suggested that the explanation for the origin of this smooth zone is diminished resolution and anomaly interference due to slow spreading rates. Our new magnetic modeling of these anomalies indicates that neither slow spreading rates alone nor slow spreading rates in combination with a decrease in geomagnetic field intensity can explain the basic character of the smooth zone. Combined with other geophysical evidence, we suggest that this smooth zone is explained by a less coherent magnetic source produced by a thinned crustal basalt layer or a non-basaltic magnetic source layer resulting from low melt supply during a period of ultra-slow spreading.

Poster II-72

Manifestations of Hydrothermal Venting at Kane Megamullion

Tucholke, Brian E.; Humphris, Susan; Dick, Henry J.

Geology & Geophysics, Woods Hole Oceanographic Inst., Woods Hole, MA

Kane megamullion was formed between about 3.3 Ma and 2.1 Ma by a detachment fault that extended up to 35 km south from the eastern inside corner of Kane FZ. The northern margin of the megamullion is coincident with the south wall of the Kane transform. The detachment exhumed sheeted dikes, diabase sills, gabbros, and mantle peridotites, as documented from imaging and sampling by ROV Jason, the autonomous vehicle ABE, and dredging. Manifestations of hydrothermal cementation and sedimentation occur on the detachment surface as: 1) cemented mounds of rock debris and sediment enriched in Mn-Fe-rich hydrothermal precipitates, and 2) cemented, slabby marlstones with Mn-Fe-rich layers. The mounds range from conical to elongate or ridge-like, with heights of 1 to 8 meters and flank slopes of 30 deg. to near-vertical. Mound compositions range from nearly pure rock debris (mostly basalt, but also gabbro and serpentinite), to polymict breccia, to nearly pure sediment. Thin-section and XRD analyses show two kinds of breccias: 1) serpentinite clasts cemented with carbonates in which microfossils are replaced by Fe-Mn oxyhydroxides, and 2) basaltic clasts cemented with quartz. Fe/Mn ratios, and trace- and rare-earth- element concentrations indicate that the Fe-Mn oxyhydroxides in serpentine breccia cement are of hydrothermal origin. The Fe-Mn oxyhydroxides in some sedimentary mounds show flow structures that mimic the form of basalt pillows. The slabby marlstones contain Fe-Mn-rich interbeds that, like the mound cement, are of hydrothermal origin. The slabs in some places are on the flanks or bases of mounds and in other places are on relatively smooth seafloor. The latter form is often cracked in linear to polygonal patterns, with upturned ridges produced at the cracks. Geochemical data indicate that some of the upper Fe-Mn layers in the slabs, as well as outer coatings on rock and breccia samples, were precipitated directly from seawater. Thus, at least in these samples, there is no evidence for recent hydrothermal venting. We propose that the debris mounds were formed where point-source fluid venting occurred through the feather edge of the detachment hanging wall near the active fault trace. The fluids cemented the hanging-wall debris and bonded it to the emerging footwall, while surrounding, unconsolidated debris wasted away down the sloping (30-40 deg.) fault surface. The mounds that consist predominantly of Fe-Mn-rich sediments probably formed updip from the fault trace. The cemented slabby marlstones may have formed in association with more diffuse venting of hydrothermal fluids through fractures in the footwall as it was exhumed and subjected to extensional bending stress in its upper part. Precipitation of hydrothermal Fe-Mn oxyhydroxides within mounds and within accumulating pelagic carbonates may have caused internal expansion that led to observed pillow-like flows and polygonal crack-and-ridge deformation, respectively. Our observations indicate that there are pathways of focused hydrothermal fluid flow that are intimately associated with major normal faults. In addition, widespread diffuse (and locally focused) fluid flow may be commonly associated with fractures formed in the emerging, bending footwalls of the faults.

Poster II-60

Life Cycle of Oceanic Core Complexes, 4: Mantle Melting Controls on a Magmatic Crustal Accretion

Unsworth, Samantha; Murton, Bramley; Taylor, Rex

S. Unsworth, B. Murton, R. Taylor, National Oceanograpy Centre, University of Southampton, Southampton, UNITED KINGDOM

Slow-spreading ridges are often characterised by variable volcanic cover, with some magmatically robust areas, and other areas which experience little volcanism. Here, spreading is accommodated via extension along low-angle detachment faults which expose mantle peridotite to form structures known as oceanic core complexes (OCC). Little is known about the mechanisms which control the transition between these two spreading states. We investigate these mechanisms in detail at the Mid-Atlantic Ridge (MAR,12°60'N-15°20'N). The geochemistry of the extrusives along the neovolcanic axis yields no evidence to suggest that melt production is reduced at OCCs, despite the lack of volcanism at these locations. However, the geochemistry of off-axis basalts, erupted at the time of OCC initiation (13°30'N, -44°95W), is substantially different. Two groups are identified here, with bimodal compositions bracketing those of the neovolcanic axis. The first consists of volatile-rich, CPX-bearing E-MORB, and the second of more N-MORB like compositions with flat REE profiles. High Yb/Lu ratios, taken as a proxy for residual garnet in the melting zone, suggest that group 1 are high-pressure, low melt fraction products. Group 2 have lower Yb/Lu ratios consistent with spinel phase melting, and compositions reflecting higher degrees of mantle melting. Group 1 have Pb, Nd and Sr isotope ratios with a HIMU flavour. These lie off the local neovolcanic axis trend, indicating that during OCC initiation; mantle sources were geochemically distinct. We conclude that this enriched and HIMU source material melts very rapidly at depth, producing the group 1 basalts, leaving the mantle column depleted and dehydrated. This promotes a brief hiatus in melting, allowing spreading to be taken up by detachment initiation. When melting resumes, Group 2 basalts are generated from the dry, depleted source. Thus, periods of low melt production at amagmatic regions, resulting directly from mantle compositional characteristics, drive the transition from magmatic to tectonic spreading. Additionally, we show that melt produced at the axis today is partially intruded along the detachment fault as dykes, reducing the amount of volcanism expressed at the axis, and giving the impression of magma starvation during the active lifetime of the core complex.

Poster I-18

Heterogeneous Seismic Velocity Structure of the Upper Lithosphere at Kane Oceanic Core Complex, Mid-Atlantic Ridge 23°17'N-23°37'N

Xu, Min; Canales, Juan Pablo; Tucholke, Brian E; DuBois, David

M. Xu, MIT-WHOI Joint Program, Woods Hole, MA; J.P. Canales, B.E. Tucholke, D. DuBois, Woods Hole Oceanographic Institution, Woods Hole, MA

We use multichannel seismic (MCS) data to constrain the shallow seismic velocity structure of the Kane Oceanic Core Complex (OCC). The high-resolution traveltime seismic tomographic models show large lateral variability in P-wave velocity within the upper ~0.5-2.0 km the lithosphere, and these variations correlate to first order with observed variations in lithology, documented by in situ basement samples and seafloor morphology. Lithological interpretation of the velocity models indicates that there is marked lateral variability in distribution of gabbroic intrusions, serpentinized peridotites, and basalts at scales of a few km to ~10 km. Serpentinized peridotites appear to dominate the central and older parts of the OCC. High-velocity gabbros are consistently (but not exclusively) present closer to the termination of the Kane detachment fault and toward the ends of the OCC. The structure of the lithosphere exhumed by the Kane detachment fault is far from the standard ophiolite-based Penrose model, and it does not show segment-centered magmatism that is commonly interpreted at slow-spreading ridges. If the gabbros exhumed toward the termination of the OCC were emplaced deep (ca. 10 km) beneath the spreading axis, they may have constituted a weak zone that focused initiation of the Kane detachment fault. Alternately, as the OCC footwall was being exhumed the gabbros may have been emplaced due to dynamic changes in melt supply, changes in mantle fertility, or decompression melting. Late-stage volcanism is clearly associated with a major high-angle normal fault that cuts the detachment surface; this volcanism may have been stimulated or enhanced by bending stresses in the bending footwall. The shape of the large-scale corrugated morphology of the OCC is nearly invariant in the dip direction across major changes in basement lithology, indicating that once established, the form of the Kane detachment fault was highly resistant to modification.

http://www.agu.org/pubs/crossref/2009/2009GC002586.shtml

BIBLIOGRAPHY

Cann, J. R., D. K. Blackman, D. K. Smith, E. McAllister, B. Janssen, S. Mello, E. Avgerinos, A. R. Pascoe, and J. Escartín (1997), Corrugated slip surfaces formed at ridge-transform intersections on the Mid-Atlantic Ridge, *Nature*, *385*, 329-332.

Cannat, M., V. Mendel, E. Ruellan, K. Okino, J. Escartín, V. Combier, and M. Baala (2006), Modes of seafloor generation at a melt-poor ultraslow-spreading ridge, *Geology*, *34*, 605-608.

deMartin, B. J., R. Reves-Sohn, J. P. Canales, and S. E. Humphris (2007), Kinematics and geometry of active detachment faulting beneath the Trans-Atlantic Geotraverse (TAG) hydrothermal field on the Mid-Atlantic Ridge, *Geology*, *35*, 711-714.

Humphris, S. E., and J. R. Cann (2000), Constraints on the energy and chemical balances of the modern TAG and ancient Cyprus seafloor sulfide deposits, *J. Geophys. Res.*, *105*, 28,477-428,488.

Karson, J. A., and R. M. Lawrence (1997), Tectonic window into gabbroic rocks of the middle oceanic crust in the MARK area near sites 921-924, *Proc. ODP Sci. Res.*, *153*, 61-76.

MacLeod, C. J., et al. (2002), Direct geological evidence for oceanic detachment faulting: the Mid-Atlantic Ridge, 15º45'N, *Geology*, *30*, 879-882.

Nuriel, P., Y. Katzir, M. Abelson, J. W. Valley, A. Matthews, M. J. Spicuzza, and A. Ayalon (2009), Fault-related oceanic serpentinization in the Troodos ophiolite, Cyprus: implications for a fossil oceanic core complex, *Earth Planet. Sci. Lett.*, *282*, 34-46.

Ohara, Y., T. Yoshida, and S. Kasuga (2001), Giant megamullion in the Parece Vela Backarc basin, *Mar. Geophys. Res.*, *22*, 47-61.

Okino, K., K. Matsuda, D. M. Christie, Y. Nogi, and K. Koizumi (2004), Development of oceanic detachment and asymmetric spreading at the Australian-Antarctic Discordance, *Geochem., Geophys., Geosyst.*, *5*, Q12012, doi:12010.11029/12004GC000793.

Searle, R. C., M. Cannat, K. Fujioka, C. Mével, H. Fujimoto, A. Bralee, and L. M. Parson (2003), FUJI Dome: A large detachment fault near 64ºE on the very slow-spreading southwest Indian Ridge, *Geochem., Geophys., Geosyst.*, *4*, 9105, doi:9110.1029/2003GC000519.

Smith, D. K., J. R. Cann, and J. Escartín (2006), Widespread active detachment faulting and core complex formation near 13ºN on the Mid-Atlantic Ridge, *Nature*, *442*, doi:10.1038/nature04950.

Tivey, M. A., H. Schouten, and M. C. Kleinrock (2003), A near-bottom magnetic survey of the Mid-Atlantic Ridge axis at 26°N: implications for the tectonic evolution of the TAG segment, *J. Geophys. Res.*, *105*, 2277, doi:2210.1029/2002JB001967.

Tucholke, B. E., M. D. Behn, R. Buck, and J. Lin (2008), The role of melt supply in oceanic detachment faulting and formation of megamullions, *Geology*, *36*, 455-458.

Tucholke, B. E., J. Lin, and M. C. Kleinrock (1996), Mullions, megamullions, and metamorphic core complexes on the Mid-Atlantic Ridge, *Eos Trans. AGU*, *77*, F724.

Tucholke, B. E., J. Lin, and M. C. Kleinrock (1998), Megamullions and mullion structure defining oceanic metamorphic core complexes on the Mid-Atlantic Ridge, *J. Geophys. Res.*, *103*, 9857-9866.

Varga, R. J. (1991), Modes of extension at oceanic spreading centers: evidence from the Solea Graben, Troodos ophiolite, Cyprus, *J. Struct. Geol.*, *13*, 517-516.