Constraints on initiation and slip (seismic/aseismic) of oceanic detachment faults: a textural and microstructural study of fault rocks from Atlantis Massif

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Project Summary

Atlantis Massif is an asymmetrically spreading oceanic core complex (OCC) on the Mid-Atlantic Ridge. Oceanic core complexes form at slow and ultraslow spreading mid-ocean ridges and are thought to accommodate asymmetric extension at these margins. Atlantis Massif core complex is composed of intrusive mafic and ultra mafic rocks, with little volcanic features or pelagic sediment present. The mafic and ultramafic rocks have been uplifted to the surface by a low-angle detachment zone that is rooted in the mantle.

Atlantis Massif is a well-studied location, but detailed work using crystallographic preferred orientation to understand the processes of fault initiation and plastic deformation associated with asymmetric spreading is lacking. Macro- and microstructural studies of samples collected by manned and unmanned submersible, and seabed rock drilling, will provide a valuable means for investigating the conditions of faulting during OCC formation. Rheological analysis of mineral deformation mechanisms (plagioclase, clinopyroxene, and olivine where present) will provide further constraints on the conditions of deformation.

Seafloor surface samples collected by the Alvin submersible from the Marvel 2000 cruise will be analyzed with electron backscatter diffraction techniques (EBSD) to identify the roles of shear zones within the core complex and along the detachment surface. In addition, IODP Expedition 357 will be collecting shallow drill cores along the detachment surface from October 2015-December 2015; samples recovered from this expedition will be analyzed with EBSD.

Ongoing questions associated with deformation at OCCs include: How do individual phases within an igneous/metamorphic assemblage accommodate strain during plastic and brittle deformation? Do oxides play a role in gabbroic pluton emplacement and subsequent deformation? Is deformation rooted within the mantle or the lower crust, or both depending on location, crustal thickness and magma supply? How does the strain profile change at and below the dominant detachment zone?

Expanding knowledge deformation at OCCs will further develop understanding of poorly understood processes at oceanic crust. Information on faulting mechanisms can also give insight into mechanisms at hydrothermal systems and add constraints to ecosystems near these systems.

Project Description

INTRODUCTION

Despite slow and ultraslow-spreading mid-ocean ridges (MORs) accounting for nearly 60% of the world's mid-ocean ridge system, their dynamics remain enigmatic. Large-offset normal faults, termed oceanic detachment faults, and their associated corrugated footwall/basement uplifts called oceanic core complexes (OCCs) have been documented along the flanks of slow and ultraslow-spreading MORs (e.g. Buck et al., 2005; Escartín et al., 2003; Hayman et al., 2011; Hansen et al., 2013; John & Cheadle, 2010; MacLeod et al., 2009;). Yet despite being relatively common (possibly underlying up to 60% of slow- to ultraslow- spreading MOR – Smith et al., 2008), their inaccessibility make them one of the least explored plate boundaries on Earth.

Ultra-slow and slow spreading ridges represent an important end-member of spreading processes. Oceanic core complexes (OCCs) form at ultra slow and slow spreading ridges and are thought to accommodate asymmetric extension at these margins (John & Cheadle, 2010). It is estimated that at least 40% or more of the Atlantic Ocean floor is formed by intertwined processes of asymmetric extension, magmatism, and detachment faulting that result in the exposure of mantle and lower crustal rocks (John & Cheadle, 2010). OCCs are exposed in volcanic-poor areas where normal detachment faults remain active over periods of 1 to 3 Myr (Cannat et al., 1995). Atlantis Massif on the Mid Atlantic Ridge (30 N°) (Figure 1) is an OCC that provides a unique natural laboratory to study deformation processes and fault zone evolution linked to asymmetric spreading at MORs.

Previous and ongoing studies at Atlantis Massif provide an excellent framework for investigating the initiation and slip history (seismic/aseismic) of oceanic detachment faults. The Alvin-assisted Marvel 2000 cruise (Blackman et al., 2002) collected seafloor samples from across the southern and central regions of the Atlantis Massif oceanic core complex (Figure 1). Deep drilling of the domal core of Atlantis Massif on Integrated Ocean Drilling Program (IODP) Expedition 304/305 drilled several holes on the central dome (Figure 1; Site U1309) in an effort to examine the nature of the detachment fault and the composition of the lithosphere in the footwall (Blackman et al., 2011). The U1309D drill core revealed a predominately gabbroic core with minimal serpentinized peridotite. In contrast, surface (submersible and dredge) samples from the southern wall (Figure 1) are deformed, altered peridotite and lesser gabbro, recording both brittle and plastic deformation in the core complex (Figure 2).

Hydrothermal fields play a key role in transporting metals and volatiles onto the ocean floor and water column. Gaining knowledge of the faulting and structure at core complexes will lead to further insight on how deformation processes are linked to fluid flow at hydrothermal vents.

Samples will be selected for detailed textural analysis using electron backscatter diffraction (EBSD) based on visible deformation features including the character of dynamic recrystallization of plagioclase, clinopyroxene (and hornblende or olivine where present); the presence of limited secondary alteration phases; and geographic location. Samples with a wide range of deformation and recrystallization textures, as well as a wide distribution over the Atlantis Massif (both spreading parallel and normal) will be selected so that changes in deformation and recrystallization mechanisms with varying mineralogy and location can be documented to provide detailed insight into the deformation processes affecting the detachment system from initiation to cessation of slip. Both high strain and low strain areas in a single sample will be analyzed to compare deformation textures over a range of total strain.

RESEARCH QUESTIONS

The transition from magmatism/ plastic deformation to brittle deformation in ocean crust (plagioclase, olivine and pyroxene rheology) is poorly understood. Investigation of this transition may lead to better understanding the formation of oceanic core complexes. This project will focus on the study of deformed gabbro and peridotite to further advance knowledge about tectono-magmatic processes and faulting mechanisms at Atlantis Massif. Unanswered questions regarding deformation at oceanic core complexes that act as drivers for this study include: How do individual phases within an igneous/metamorphic assemblage accommodate strain during plastic and brittle deformation? Do oxides play a role in gabbroic pluton emplacement and subsequent deformation? Is deformation rooted within the mantle or the lower crust? How does the strain profile change at and below the dominant detachment surface?

RESEARCH PLAN

Sample material will come from both spreading-parallel, and ridge-parallel sites, to encompass the widest range in fault rock type associated with the oceanic detachment fault system. I will use samples from the MARVEL 2000 cruise (Blackman et al., 2002; Schroeder & John, 2004), as well as shallow core samples recovered from the denuded fault drilled during ongoing IODP Expedition 357 (http://www.eso.ecord.org/expeditions/357/357.php).

Goals of this work are as follows:

i) Macro-structural characterization of fault rocks, based on shore-based core descriptions and seafloor observations, and ii) microstructural characterization of naturally deformed samples by investigating phase composition, grain size distribution, grain shape, lattice preferred orientations (LPO) in plagioclase, pyroxene (± olivine if present), compared to undeformed host rocks.

ii) Overprinting relationships between different fabrics will be assessed; deformation mechanisms based on grain shape, recrystallized grain size distributions, LPO, and any association of a fabric with retrograde mineral assemblages. Electron backscatter diffraction (EBSD) will quantify deformation fabrics and grain sizes, and together determine deformation mechanisms (e.g., transition from dislocation to diffusion creep).

Data to be collected –

1) Macroscopic brittle deformation - oriented large thin sections for analysis of particle size distributions and to infer frictional properties using existing methods.
2) Macroscopic semi-brittle and viscous deformation - oriented large thin sections to measure the SPO (shape-preferred orientation) and LPO of plagioclase, pyroxene (± olivine if present) from the least altered samples, using EBSD. Thin sections will be cut normal to foliation and parallel to lineation/slip to assess deformation mechanisms and slip systems.

Analytical work will be conducted using an FEI Quanta FEG 450 field emission SEM, with Oxford HKL EBSD system housed at the University of Wyoming.

Thin sections will be cut from collected drill core samples and petrographically analyzed. The Scanning Electron Microscope (Electron Backscatter Diffraction technique- EBSD) at the University of Wyoming Geology and Geophysics Department will be used to analyze the crystallographic orientation of previously collected samples (Marvel 2000 cruise) and planned shallow drill core samples (IODP Expedition 357). Observed textures and structures will be correlated with previously analyzed petrological and chemical data collected by Schroeder & John (2004).

EXPECTED RESULTS

Conduct a detailed microstructural and petrographic analysis of fault rocks collected from the surface of Atlantis Massif detachment system to illuminate oceanic detachment fault processes. Hansen et al., (2013) examined the Kane detachment fault along the Mid-Atlantic Ridge (23 N°) with microstructural analysis in order to become familiarized with deformation processes and rheological properties at the Kane core complex. Previous studies have noted a lack of plastic deformation in gabbroic sections of the U1309D drill core (Halfpenny & Prior, 2009). Preliminary examination of thin sections from the Marvel 2000 cruise appears to show a significant amount of plastic deformation in all lithologies. EBSD techniques will be employed to confirm whether deformation is brittle or plastic in shear zones within the Atlantis Massif core complex and along the detachment surface.

This study will gain insight into brittle/plastic deformation mechanisms at Atlantis Massif. Knowledge of the crystallographic fabric within the detachment zone will constrain the processes leading to detachment zone formation and progression. The results/conclusions from this study will be compared to continental margins and other oceanic core complexes in order to investigate differences of deformation, specifically at the brittle/ductile transition.

BROADER IMPACTS

Expanding knowledge about formation and deformation at OCCs will further develop understanding of poorly understood processes at oceanic crust. Information on faulting mechanisms can give insight into fluid flow within and along detachment surfaces associated with core complexes (Boschi et al., 2006, Hirose & Hayman, 2008, McCaig & Harris, 2012). Faults may be the main conduit for crust/ocean interaction, allowing for the exchange of minerals in seawater, this exchange may have serious implications for the overall chemistry of the oceans (Castelain et al., 2014).

Hydrothermal vents harbor unique organisms that may be an analog to early life on earth (Früh-Green et al., 2015). Understanding how fluids move within hydrothermal systems can give clues to how life has evolved at these isolated systems. Hydrothermal systems are also interesting because they are often associated with metal deposits. Some of these deposits may have economic value (Boschi et al., 2006).

Low angle detachment faults associated OCCs are thought to be analogous to early transition stage continental rifts/ continental margins (Dean et al., 2014). Understanding the dynamics of continental margin formation and basement level structure is key for development of natural resources along these margins.

BUDGET

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Items	Amounts/Rates	Price
Thin Sections	30 Thin sections*$60 each	$900
SEM/EBSD	20 Samples*$350 each	$7,000
Polishing	20 Cloths ($25), 2 Bottles of polishing fluid $(500)	$525
Travel-Bremen, GER	3-5 nights+ round trip flight	$3,000
		Total=$11,425

The proposed budget includes SEM/EBSD runs that will be necessary to collect macro and micro structural data. Polishing upkeep is also necessary for preparation of thin sections for analysis. Additional thin sections will need to be made from the samples collected during Expedition 357; therefore funds will be required to prepare these thin sections. A trip to Bremen, Germany would be highly beneficial to this study. This trip would be to the IODP Drill Core Repository in Bremen. Visiting the Repository would aid in analysis of macro scale textures within the rocks recovered from IODP hole U1309D and the rocks recovered in the Marvel 2000 cruise.

FIGURES

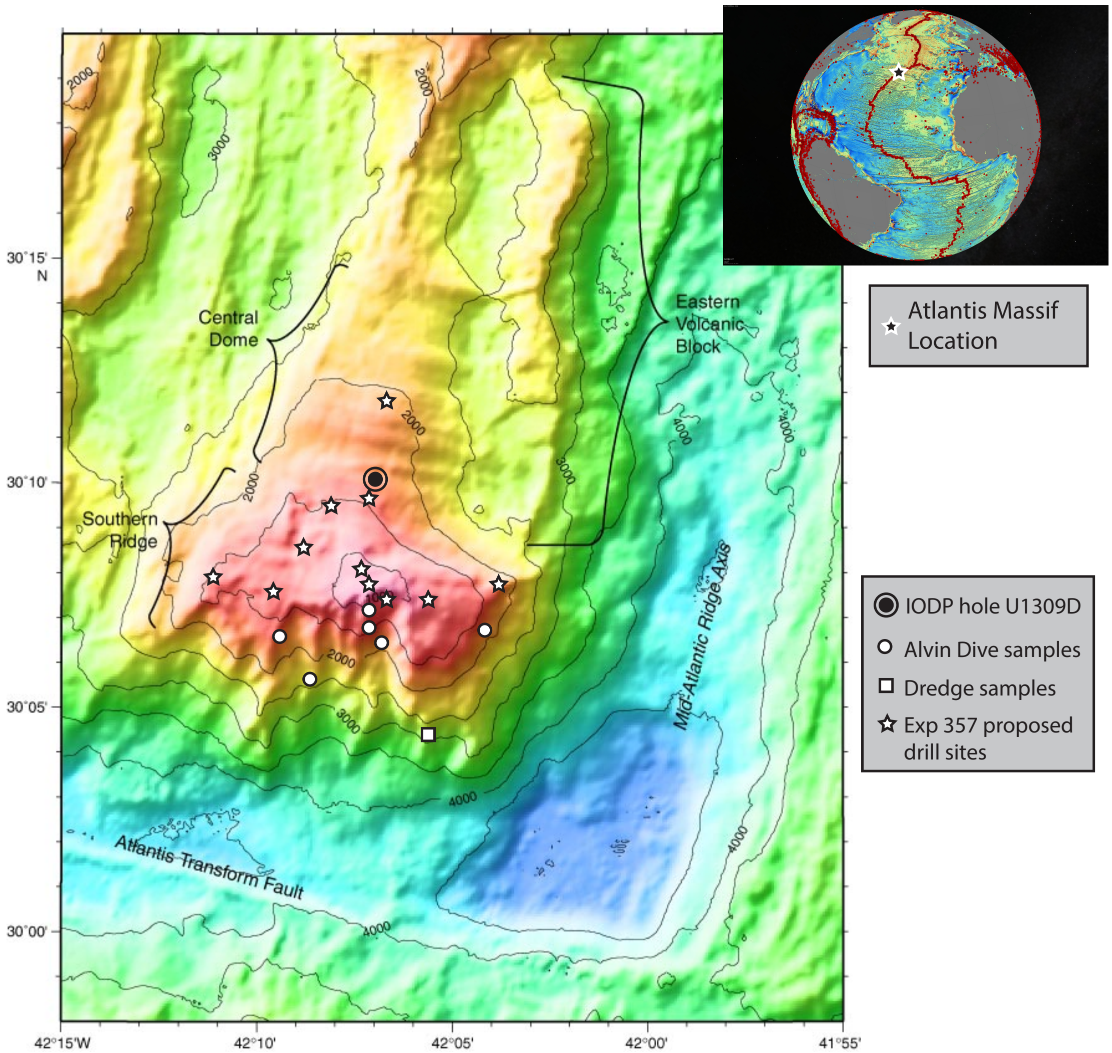

FIGURE 1- IODP drill hole, sample locations and proposed drill sites on the dentral dome and southern wall of Atlantis Massif.

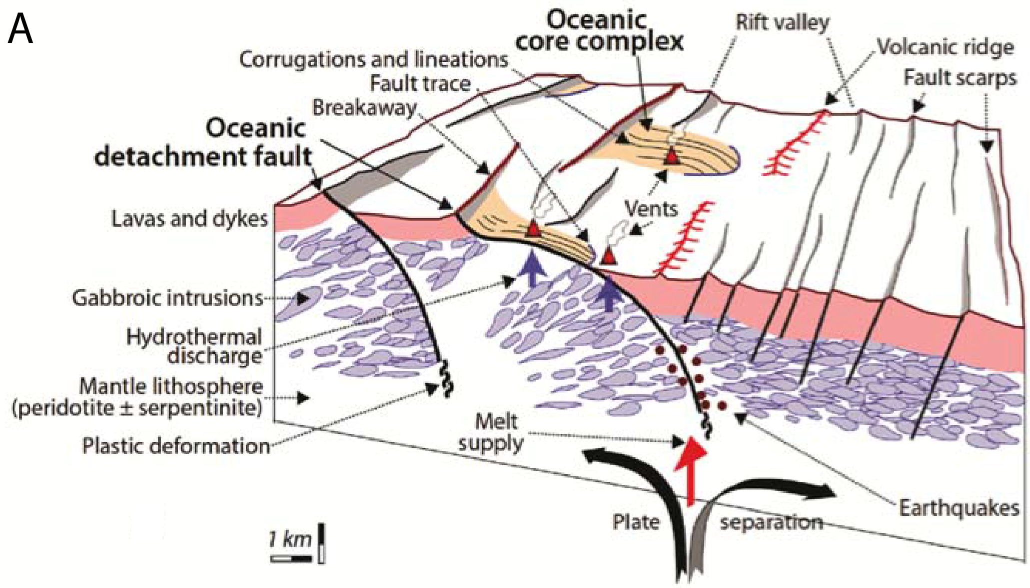

Figure 2. -A. Conceptual sketch of lithosphere accretion and the tectono-magmatic evolution of heterogeneous lithosphere and denudation of mantle rocks as detachment faulting progresses and oceanic core complexes are formed at slow-spreading ridges (from 2010 Chapman Conference Report "Detachments in Oceanic Lithosphere: Deformation, Magmatism, Fluid Flow, and Ecosystems").

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