**Geologic implications of seafloor character and carbonate lithification imaged on the domal
core of Atlantis Massif**

John A. Greene¹, Masako Tominaga¹, and Donna K. Blackman²

¹ Department of Geological Sciences, Michigan State University, East Lansing, MI

² Scripps Institution of Oceanography, University of California, San Diego, La Jolla, CA

ABSTRACT

We document the seafloor character on Atlantis Massif, an ocean core complex located at 30°N on the Mid-Atlantic Ridge, with an emphasis on the distribution of carbonate features. Seafloor imagery, near-bottom backscatter, and bathymetry were analyzed on the Central Dome and the Western Shoulder of the exposed footwall to the detachment, and on the Eastern Block, a hanging wall to the fault. We merged *Argo II* still images to produce photo-mosaics and evaluated these together with video imagery, acoustic reflectivity, and basic rock composition. The seafloor was classified as unconsolidated sediment, lithified carbonate crust, consolidated carbonate cap, exposed basement, or rubble, and the spatial distribution of each type was assessed. Unconsolidated sediment, exposed basement, and rubble were documented in all three regions studied. Lithified carbonate crust was also present on the Western Shoulder and eastern Central Dome. Consolidated carbonate cap was found on the Eastern Block. The formation of the carbonate rock is interpreted to reflect precipitation and/or sediment cementation via fluids derived from serpentinization. Both processes occur at the nearby Lost City Hydrothermal Field. The newly documented locations of seafloor carbonate lithification therefore mark pathways of past, possibly recent, fluid flux from subsurface water-rock reaction zones and represent an additional constituent of the carbon cycling hosted by oceanic lithosphere.

1. Introduction

One of the most significant contributors to the long-term global carbon cycle involves the transfer of carbon between subsurface rock formations and the hydrosphere and atmosphere on a timescale of millions of years (Berner, 2003). Carbonate precipitation and accumulation in marine settings is one

component of this global carbon cycle budget (Sun and Turchyn, 2014). The extent of carbonate deposition and preservation on the seafloor varies with local sedimentation rate and seafloor depth (Weaver and Rothwell, 1987), as well as tectonic setting. Local processes can enhance rates within active areas such as mid-ocean ridge axial zones (e.g., Delacour et al., 2008a; Früh-Green et al., 2003; Kelley et al., 2001, 2005; Schroeder et al., 2002), back arc magmatic systems (Snyder et al., 2001), or the shallow ridge flanks where low-temperature hydrothermal circulation continues long term (Alt and Teagle, 1999; Coogan and Gillis, 2013).

Oceanic core complexes (OCC; Cann et al., 1997; Karson, 1990; Tucholke et al., 1998) develop during sustained periods of detachment faulting at slow spreading ridges ($< 20\text{mm/yr}$, half spreading rate) (Cannat et al., 2006; Escartín et al. 2008; Smith et al., 2006). Asymmetric spreading, where one flank exhibits detachment faulting, is estimated to occur along approximately 50% of the Mid-Atlantic Ridge (MAR) axis (Escartín et al., 2008). Since their discovery, OCC exposures have provided information on the formation and evolution of the slow-spreading axial environment, including detachment faulting (Blackman et al., 1998, 2002, 2011; Dick et al., 2008; Canales et al., 2008; Henig et al., 2012; Karson et al., 2006; MacLeod et al., 2009; Mallows and Searle, 2012; Morris et al., 2009; Schroeder and John, 2004; Tucholke et al., 1998, 2001), subsurface fluid flow and associated serpentinization processes (Andreani et al., 2014; Blackman et al., 2002, 2011; Delacour et al., 2008a, 2008b; Früh-Green et al., 2003, 2004; Karson et al., 2006; Kelley et al., 2001; McCaig et al., 2010; Schroeder et al., 2002; Tucholke et al., 2013), and the accompanying biogeochemical activities (Andreani et al., 2014; Früh-Green et al., 2003, 2004; Karson et al., 2006; Kelley et al., 2001, 2005; Schroeder et al., 2002; Tucholke et al., 2013). However, very few studies report on the sedimentary carapace of OCCs (Karson et al., 2006; Tucholke et al., 2001, 2013).

At Atlantis Massif, an OCC located at the inside corner of the MAR and the Atlantis Fracture Zone (Fig. 1), the Lost City Hydrothermal Field (LCHF) is a prominent off-axis hydrothermal vent system, where moderate temperature hydrothermal fluid resulting from water-rock interaction during *in situ* serpentinization processes has been thought to play a critical role in building the whole vent

system (Früh-Green et al., 2003; Kelley et al., 2001; Schroeder et al., 2002). In addition to serpentinization related carbonation at the LCHF (Früh-Green et al., 2003; Kelley et al., 2001; Schroeder et al., 2002), the existence of other carbonate locations has been reported on other areas of Atlantis Massif (Blackman et al., 2002; Karson et al., 2006), as well as at other OCCs (Tucholke et al., 2013). Yet, the origin, distribution, and implications of these carbonate deposits have not been systematically assessed or explained.

In this paper, we examine the nature and distribution of seafloor sediments using near-bottom photo mosaics and video imagery from the Central Dome, Eastern Block, and Western Shoulder of Atlantis Massif. The available seafloor data required to evaluate the effectiveness of this method is sparse, but our findings provide new insight about their possible origin and some implications regarding subsurface lithology and geological processes.

2. Background

Atlantis Massif developed via detachment faulting rooted within the axial zone of the MAR at 30°N. Slip along the fault may have accommodated most of the 24 mm/yr plate spreading (Pariso et al., 1996) during the period that the detachment was active, unroofing 1.2 Ma intrusive crust in the present-day domal core (Grimes et al., 2008). The adjacent, back-tilted volcanic block to the east of the Central Dome is the hanging wall to the detachment (Cann et al., 1997). The broader, shallower Southern Dome displays only small klippe atop the exposed detachment fault (Blackman et al., 2002). The Western Shoulder differs from the seafloor to the east along the southern dome, where corrugations and striations similar to the Central Dome occur. The LCHF, hosted in serpentinized peridotite, is located just below the southern peak of the massif (Kelley et al., 2001). The Atlantis Transform Fault bounds the south side of the massif, giving rise to its maximum relief of 4 km.

Dredging and Alvin sampling (Blackman et al., 2002; Cann et al., 1997) and Integrated Ocean Drilling Program (IODP) coring (Blackman et al., 2011) indicate that the core of the massif is comprised of gabbroic and ultramafic rock (Boschi et al., 2006; Karson et al., 2006). Seismic analyses indicate that

gabbroic rock, which dominated the 1.4 km section recovered from IODP Hole U1309D on the Central Dome, probably occurs in fewkm-wide bodies (Canales et al., 2008) that favor the eastern part of both the Southern and Central domes (Henig et al., 2012). The extent of serpentinized peridotite within the domal core is not certain, but Henig et al. (2012) determine from P-wave velocity gradients that the Southern Dome is dominated by this composition, except for beneath the Eastern Shoulder, which has a gabbroic signature (near surface seismic velocity and gradient).

Karson et al. (2006) describe a thin cap of sedimentary breccia and overlying pelagic limestone mapped along the top rim of headwall scarps where the Southern Dome drops off toward the transform valley. These deposits, < 3 m thick, have been inferred to cover the entire Southern Dome, though visual coverage is concentrated between longitudes 42°06.3' and 42°08.5'W on the south rim. This interval is west of where Henig et al. (2012) determined that seismic velocities/gradients correspond to a gabbroic portion of the dome, and Karson et al. (2006) concluded that the subseafloor rock in the area was ~70% serpentinized peridotite. The pelagic limestone was observed to grade upward into unconsolidated pelagic ooze. Früh-Green et al. (2003) reported that lithification of the pelagic limestone was rapid. They interpreted subparallel tubular structures in the deposits as fossilized paths of diffuse hydrothermal fluid flow.

3. Methods

3.1 Image processing

We used *Argo II* digital still photos and videos, *Alvin* videos and rock samples, *Simrad/SeaBEAM2000* swath bathymetry data, and a combined *Tobi* and *DSL-120* side-scan sonar mosaic (Blackman et al., 1998, 2002) to examine three regions of Atlantis Massif: the Central Dome, Eastern Block, and Western Shoulder (Fig. 1). Data from two *Argo II* tows over the Central Dome (tracks A39 and A40), one tow over the Western Shoulder (track A41), and one tow on the Eastern Block (track A43) were analyzed to determine the geological character of the seafloor (Fig. 2A). *Argo II* track A39, located on the eastern side of the Central Dome, gradually moves upslope over a depth range of approximately

1,900 to 1,600 m (Fig. 2B). *Argo II* track A40, on the western side of the Central Dome, consisted of an upslope path to a local peak with a depth of approximately 1,450 m followed by a downslope path extending to a maximum depth of around 1,650 m. A steeper slope was found near the local peak, and the slope became shallower as the trackline moved to deeper water (Fig. 2A). Like track A40, *Argo II* track A41 followed an upslope then downslope path, covering depths that ranged from approximately 1,400 to 1,500 m (Fig. 2C). The *Alvin* dives used in this study are over the Central Dome and Eastern Block of the massif (dives 3641, 3642, 3643, 3644, and 3653). We used data from these dives to examine the seafloor character and basic rock types for comparison with our *Argo II* observations. The *Tobi* and *DSL-120* side-scan sonar followed regional, looped tracks that provided near total coverage of the acoustic reflectivity of the seafloor on the massif (Blackman et al., 2002, their Figs. 2 and 3). The *DSL-120* side-scan sonar (120 kHz) has a resolution of ~2 m and the *Tobi* side-scan sonar (30-32 kHz) has a resolution of several meters (Blackman et al., 1998, 2002).

We merged the *Argo II* digital still photographs to produce 726 photo mosaics for subsequent interpretation using the photomerge tool in Adobe Photoshop. Because of the significant overlap of the seafloor captured in consecutive photos, we used prominent shared features to determine the alignment and position necessary to create a near seamless, continuous mosaic. The typical mosaic consisted of around 12 images, showing an area of the seafloor a few meters wide and ~10 m long.. The length of the mosaic was dependent on the clarity of image and the presence of distinct features necessary for the pattern recognition software to achieve a reliable merge. To create longer mosaics, we merged multiple sequential mosaics when the features provided enough overlap to match. We used the timestamp for each photo and resulting mosaic to merge the navigation data acquired via a seafloor transponder network deployed on the massif during the cruise (Blackman et al., 2002).

3.2 Image classification/interpretation

We classified the seafloor covered by *Argo II* into morphological groups based on visual character of the seafloor, including color, tone, shape, and texture. It should be noted that the lighting

present in the photographs was carefully assessed because it varied from photo to photo and could influence the color and tone of the features, along with creating shadows that could result in erroneous interpretation of the seafloor morphology. The morphological groups present within each mosaic were outlined and color-coded based on the classification. The orientations of sediment ripple marks were also annotated when present. The *Argo II* video was analyzed in conjunction with the corresponding photo mosaics to aid in the annotation. This allowed for multiple perspectives of the same area when examining the seafloor.

Using the previous studies at Atlantis Massif (described in Section 2), analogous studies at other massifs (Tucholke et al., 2013), and available *Alvin* rock sample descriptions, we created an interpretation for the composition of the morphological groups. *Alvin* video was used to examine the rock samples *in situ* for comparison to the local seafloor classifications.

We also analyzed the distribution of these morphological groups in a broader context. We examined the *Tobi* and *DSL-120* side-scan sonar mosaic, seafloor slope gradient, downslope direction, and bathymetry maps for direct comparison. Further examination of the *Alvin* video was also used to gain a general understanding of the dominant seafloor character for the areas outside of the *Argo II* track lines.

4. Results

4.1 Morphological classification

We classified seafloor character into five morphological groups: unconsolidated sediment, debris, exposed basement, “pancake shaped” features, and a “cliff cap”. We established these morphological groups based on observations and descriptions made in Blackman et al. (2002) and Tucholke et al. (2013).

Unconsolidated sediment was ubiquitously observed within our study area (Figs. 3, 4, 5, 6). Ripple marks with various degrees of abundance and orientation were observed at some places (Figs. 3 and 6A), indicating that the sediment is mobile and the distribution may be influenced by bottom currents, although no systematic flow pattern was recognized on the basis of ripple pattern orientations.

Fragments of rock strewn across the seafloor were classified as “debris”. This class was also ubiquitously observed in our study area. The debris fragments are rounded or angular with a dark grey to black color in the *Argo II* photos. The abundance and size/spacing of the debris pieces vary. Some areas of debris exhibited a banded arrangement (Fig. 6A), while others had a field of scattered fragments (Fig. 3).

Overall, exposed basement rock is rare on the top of Atlantis Massif (Blackman et al., 2002). Exposed basement was mostly absent in our study areas, except for a few localities (Figs. 4A, 4B, and 5). The exposed basement was dark grey to black in the *Argo II* imagery. Many of the outcrops were observed to be expansive features, with the entirety not visible in a single mosaic. Some had smooth faces, while others exhibited fractures.

The “pancake shaped” features followed the observations and descriptions made by Tucholke et al. (2013) at Kane Megamullion. Visually, they were categorized as being thin, platy flat slabs (Figs. 3 and 6). They typically occurred within areas of unconsolidated sediment, and were often partially buried by the sediment or overlain with debris. They are dark grey in the *Argo II* imagery and could exhibit a smooth or rough texture.

The morphological group described as a “cliff cap” was a laminated, structured mass of light colored rock. This was exclusively found on the Eastern Block, overlying the scarp shown in the imagery (Fig. 5).

4.2 Lithological classification

We identified and assigned a lithology to each of the morphological groups. This was completed using previous studies of Atlantis Massif, *Alvin* rock sample identifications, and analogous studies at other massifs.

The unconsolidated sediment blanketing much of the study areas (Figs. 3, 4C, and 6) was identified as pelagic ooze. This identification was consistent with Blackman et al. (2002) and Schroeder et al. (2002). Additionally, IODP Expedition 304/305 obtained a few meters of unconsolidated sediment

identified as calcareous microfossil ooze at IODP Holes U1309A, U1309B, and U1309G (Blackman et al., 2006).

On the Central Dome, serpentinized peridotite, basalt, and carbonate samples were collected by *Alvin*, while on the Eastern Block, only basalt was collected (Blackman et al., 2002, their Table 1). The “debris” visually matched the basalt and serpentinized peridotite samples, and was also identified as such in Blackman et al. (2002).

The few instances of exposed basement observed included a scarp exposing fractured pillow basalt and weathered pillow basalt. These were identified through our systematic visual analysis and are consistent with the interpretation of Blackman et al. (2002).

The “pancake shaped” features were visually similar to the features where *Alvin* collected carbonate samples. They are in line with the interpretation reported in Blackman et al. (2002) for Atlantis Massif and Tucholke et al. (2013) at Kane Megamullion, leading to the classification as a lithified carbonate crust.

The “cliff cap” was typically dusted with unconsolidated sediment. However, the “cliff cap” could be differentiated from the unconsolidated sediment through our observation that the rock holds its structure even when portions are extended over the edge of the scarp (Fig. 5). With this, it is suggested that the sediments are consolidated, and the “cliff cap” was identified as a consolidated carbonate cap.

4.3 Geographical distribution of lithological groups

4.3.1 Central Dome

Two *Argo II* tows (tracks A39 and A40) and four *Alvin* dives (dives 3641, 3642, 3643, 3653) were located over the Central Dome of Atlantis Massif (Fig. 2A). Our compilation of mosaics for this region shows the presence of pelagic ooze, debris, lithified carbonate crust, and exposed basement material, with many individual areas displaying multiple lithologies in different combinations.

We found that unconsolidated pelagic ooze blanketed much of the area, with fields of basaltic or serpentinized peridotite debris interspersed (Fig. 3). On and near the *Argo II* track A39, we identified

areas of lithified carbonate crust. Some of this crust occurred as a single, meter scale patch, while the rest consisted of many smaller patches grouped within a few meters of each other (Fig. 3). The lithified carbonate crust is distributed ubiquitously over this entire trackline (Fig. 2B). The remainder of seafloor imaged along this trackline primarily consists of unconsolidated pelagic ooze and/or debris.

Expansive, exposed basement material was present on the steeper slope area near the local peak on the Central Dome *Argo II* track A40 (Figs. 4A and 4B). Downslope, the seafloor changed to debris and unconsolidated sediment as the slope became shallower and the seafloor depth increased (Fig. 4C). No lithified carbonate crust was found in the imagery analyzed from this track.

4.3.2 Eastern Block

Mosaics from the *Argo II* track A43 and video from *Alvin* dive 3644 crossed the Eastern Block and its edge at the rift valley (Fig. 2A). The Eastern Block was the deepest section studied, with an approximate depth of 2,800 m at the top of the scarp imaged by both the *Alvin* dive and *Argo II* track. The scarp face imaged consisted of an accumulation of pillow basalts. The top of the scarp was covered in a laminated, consolidated carbonate cap with an overlying dusting of unconsolidated pelagic ooze (Fig. 5). The base of the scarp was piled with basaltic debris dusted with unconsolidated pelagic ooze.

4.3.3 Western Shoulder

The Western Shoulder of Atlantis Massif was mapped by only one *Argo II* tow (track A41) (Fig. 2A). We observed that the seafloor dominantly consisted of unlithified pelagic ooze or fields of rounded pillow basalt debris, with some weathered basalt exposed and only five instances of the lithified carbonate crust (Fig. 6). The lithified carbonate crust, although sparse, occurred ubiquitously throughout the entire track, with no confinement to a particular section (Fig. 2C).

4.4 Lithified carbonate bathymetry/slope/sonar comparison

We compared the lithified carbonate distribution to the bathymetry, slope angle, and sidescan sonar to determine if these physical qualities hold any constraint on where lithification does/does not occur. A bathymetry map was used to compare the seafloor depth with our lithified carbonate crust locations. The map consisted of *Simrad/SeaBEAM2000* swath bathymetry data with a 100-m grid spacing created using the minimum curvature surface algorithm with tension in Generic Mapping Tool (GMT) (Wessel and Smith, 1991) by Blackman et al. (2002). The lithified carbonate crust was observed in a depth range from ~1,600 to 1,900 m on the Central Dome (*Argo II* track A39) and 1,400 to 1,500 m on the Western Shoulder (*Argo II* track A41) (Fig. 2). This produces an approximate depth range of 1,400 to 1,900 m for the lithified carbonate crust. However, this is also the entire combined depth range for both tracks. Although *Argo II* track A39 had significantly more locations, both tracks had a fairly equal distribution of the lithified carbonate crust at all depths. Therefore, the lithified carbonate crust can exist throughout the range studied without any apparent preference for a particular depth. No lithified carbonate crust was identified on *Argo II* track A40, despite it being within the depth range of crust lithification elsewhere on the massif. Because of this, depth is not likely to be the reason for the absence of the lithified carbonate crust at *Argo II* A40 or the presence at the other locations.

From the same bathymetry data, slope angles were calculated and used to compare the seafloor slope with our lithified carbonate locations. *Argo II* tracks A39 and A41 were located over seafloor with a slope of less than 20 degrees (Fig. 7), and hence, our interpretation is limited to observations within this angle range, limiting the determinable constraints of slope on lithified carbonate crust formation. It can be noted that the lithified carbonate crust locations are not found on the steepest part of *Argo II* track A41 on the Western Shoulder; however, there are only five carbonate locations present so there is not sufficient evidence to show that this steeper slope is restrictive.

The average slope angle for *Argo II* track A40 is slightly steeper than that of *Argo II* tracks A39 or A41, but it contains many parts within the range of 20 degrees or less. Within the grid size of 100 m (Blackman et al, 1998), portions could be locally flatter or steeper than the calculated grid cell angle, creating even more difficulty in determining the angle on which carbonate lithification occurs.

In addition, a combined *Tobi* and *DSL-120* sidescan sonar mosaic was used to determine if the backscatter character of the seafloor matched the distribution of the lithified carbonate crust and consolidated carbonate cap. Acoustically reflective seafloor such as hard lithified or consolidated carbonate would be light in the sidescan sonar mosaic (Blackman et al. 2002). We found that no one-to-one correlation with the lithified carbonate crust or consolidated carbonate cap and the backscatter character can be identified. Many of the patches of crust classified in our study are too small to be identifiable in the sidescan, but not all are. *DSL-120* has a resolution of ~2 m while *Tobi* has a resolution of several meters (Blackman et al., 1998, 2002). Backscatter return from other, adjacent features could also obscure the return from the lithified carbonate crust patches.

Structural features such as the spreading parallel corrugations and striations of the Central Dome are identifiable in the combined *Tobi* and *DSL-120* sonar mosaic (Blackman et al., 2002, their Figs. 6 and 14; Blackman et al., 2009, their Fig. 3). Blackman et al. (2009) questions whether areas of lithified sediment create acoustic contrast and produce the striations observed in the sonar mosaic. Based on the comparison with the identified striations, ~39% (17 of 44) lithified carbonate crust locations on *Argo II* track A39 appears to correlate. Overall, we do not have enough coverage to confirm or rule out the proposed correlation between the lithified carbonate crust and the striations present in the sonar.

4.5 Hydrothermal fluid seepage

It should be noted that we found no visual evidence of hydrothermal fluid seepage from the seafloor in our videos. However, given our limited coverage and that low temperature, diffuse hydrothermal flow can have clear fluids (Dias et al., 2011), this does not mean that flow is absent or that flow has ceased.

5. Discussion

The observed carbonate sediments on the Central Dome, Eastern Block, and Western Shoulder of Atlantis Massif are an unexpected mix of lithified and consolidated sediment emerging from

unconsolidated pelagic ooze regardless of topography (see Section 4.4), which is discrepant from the archetypical unconsolidated pelagic ooze accumulation and distribution predicted throughout the North Atlantic basin (Tucholke, 1986). A possible origin of such a mixture could involve sediment compaction and diagenesis solely through burial as expected within the pelagic sediments. However, the lithified and consolidated carbonates we observed in our study areas occur as surficial features sporadically emerging within the unconsolidated sediment cover. Compaction of pelagic carbonate sediments requires burial of the sediments to a depth of ~100-400 m (Goldhammer, 1997). Subsequently, the rock would have to be re-exposed to the surface following diagenesis in order for us to observe them using the deep submergence imaging. Blackman et al. (2002) estimated that the age of Atlantis Massif's lithosphere to be within an age range of 0.5 to 2.0 Ma. Grimes et al. (2008) date rocks in the footwall exposed via detachment faulting at ~1.2 Ma. Therefore, the age of the massif would be insufficient to allow for burial and diagenesis, as crust along the MAR that is younger than ~5 Ma has less than 100 m of sediment accumulation, except for that in small sediment ponds (Tucholke, 1986). Additionally, the small amounts of carbonate sediment recovered from IODP Holes U1309A, B, and G (Blackman et al., 2006) and dusting on the Eastern Block indicate that this scenario is unlikely.

We propose two possible scenarios for processes that formed the observed lithified carbonate crust and consolidated carbonate cap on Atlantis Massif: (1) precipitation and/or, (2) sediment cementation, both of which have been observed at the LCHF on top of the Southern Wall of the massif. At the LCHF, the precipitation and cementation processes of carbonate formation involve hydrothermal fluids that are derived from *in situ* serpentinization, which contribute to (Allen and Seyfried, 2004; Lowell and Rona, 2002) and likely control (Früh-Green et al, 2003; Kelley et al., 2005) the venting of Ca and H₂-rich hydrothermal fluid with a high-pH (9-11) and a temperature range from 40° to 91°C (Kelley et al., 2005). The carbonate precipitation observed at the LCHF is notably in the form of up to 60 m tall vent chimneys protruding from the seafloor, and additionally through precipitation either on outcrop surfaces, protruding from outcrops, filling outcrop cavities, and as carbonate veins (Delacour et al., 2008a; Früh-Green et al., 2003). These precipitation processes occur in areas of more focused fluid

venting, like the South Wall (Schroeder et al, 2002), and formed during the hydrothermal activity occurring over at least 30,000 years (Früh-Green et al., 2003). Meanwhile, flat-lying, lithified carbonate sediment formed through the cementation of deposited pelagic sediment has also been observed at the LCHF (Früh-Green et al., 2003; Schroeder et al., 2002). This cementation is interpreted to have initiated during diffuse venting of hydrothermal fluids derived from serpentinization, which then percolate through the pelagic sediments on the seafloor (Früh-Green et al., 2003; Schroeder et al., 2002). Thus, cementation at the LCHF is reliant on seawater circulation to the subsurface serpentinization reaction zones (Früh-Green et al., 2003). At Kane Megamullion, similar processes have been noted where hydrothermal fluid has cemented pelagic carbonate deposits (Tucholke et al, 2013).

The lithified carbonate crust and the consolidated carbonate cap deposits elsewhere on Atlantis Massif could be formed through a process similar to the precipitation and/or cementation observed at the LCHF. In our survey areas, because there is no visual evidence of hydrothermal fluid seepage from the seafloor, it is impossible to determine the timing and duration of these processes with visual imagery. As at the LCHF, carbonate precipitation and/or cementation can either be ongoing, or could have ceased (Schroeder et al. 2002); nevertheless, the existence of the carbonate features observed in our study should manifest the link between surface carbonation deposition and lithification processes and subsurface hydrothermal systems.

The consolidated carbonate cap deposit is observed on the Eastern Block. This consolidated carbonate cap exhibits internal layering, with a thin layer of overlying, unconsolidated pelagic ooze (Fig. 5). This sediment structure suggests that the sediment accumulation occurred in distinct layers, which could subsequently have been indurated. The formation of the consolidated carbonate cap could be facilitated by serpentinization-driven hydrothermal fluid that has cemented pore spaces in the unconsolidated sediments, potentially delivered through the fault that caused the scarp on the Eastern Block.

The most prevalent distribution of lithified carbonate crust in our study area is on the eastern side of the Central Dome (*Argo II* track A39), outcropping from unconsolidated pelagic ooze. The subsurface

formation in this area is dominantly composed of a gabbroic core (Blackman et al., 2006; Henig et al., 2012), although the possible juxtaposition of ultramafic and gabbroic formations within the basement is still debated (Ildefonse et al., 2007). Hydrothermal systems hosted by this formation could be related to the alteration of the gabbroic core and/or serpentinization of interfingering ultramafic formations (Andreani et al., 2014; McCaig et al., 2010; Blackman et al., 2014). The origin and extent of possible hydrothermal circulation processes in the subsurface of OCCs and their exact fluid pathways have been discussed extensively in previous studies; yet, the direct evidence remains very sparse except for fluid seepage found from seafloor observations (Andreani et al., 2014; Delacour et al., 2008a, 2008b; Escartín et al., 2008; Früh-Green et al., 2003; Karson et al., 2006; Kelley et al., 2001, 2005; Ludwig et al., 2006, 2011; Macleod et al., 2011; Tucholke et al., 2013). It has been observed that nearly all ultramafic and gabbroic rocks recovered from the upper 800 m of IODP Hole U1309D on the Central Dome, located in close proximity to our prevalent lithified carbonate crust at *Argo II* track A39 (Fig. 2B), have been affected by alteration (Expedition Scientific Party, 2005). This subsurface alteration observed at the site shows that fluid must have circulated to depths where it interacted with the rock formation, likely using faults or fractures as conduits for flow. Although we obtained no visual evidence, the presence of hydrothermal circulation in the vicinity of the lithified carbonate crust in the Central Dome survey area cannot be excluded because low temperature diffuse hydrothermal flow that includes products of serpentinization can have clear fluids (Dias et al., 2011). Additionally, the formation of lithified carbonate crust at the Central Dome could have occurred in the past when the current carbonate crust locations were in an area of fluid flow, such as at the termination of the detachment fault zone (McCaig et al., 2007), followed by the carbonate crusts being rafted off axis to their current positions as the massif continued to evolve. We propose that hydrothermal fluid circulation resulting from serpentinization processes hosted within ultramafic lenses in the core of Atlantis Massif led to lithification of carbonate oozes to form the lithified crust on the eastern Central Dome.

If the processes forming the carbonate features observed in our study areas are similar to either or both of the hydrothermally driven carbonation processes of the LCHF, the locations of these lithified

carbonate crusts and consolidated carbonate caps mark seafloor that was linked to regions of subsurface serpentinization via hydrothermal fluid flow. Therefore, these features denote an additional component of the carbon cycling hosted by oceanic lithosphere.

To get a sense of the potential amount of carbon preserved in lithified sedimentary caps at Atlantis Massif, we use our new observations as a guide. We calculated the mass of carbon contained in an upper end-member scenario where a ubiquitous, 1-m thick layer of lithified carbonate covers various structural components of the massif. Scenario 1 encompassed the entire dome (Southern and Central), but excluded the Eastern Block. This scenario had an approximate surface area of 90 km². Scenario 2 was defined as just the corrugated portion of the Central Dome, the entirety of the Southern Dome, and Eastern Block, and it had an approximate surface area of 110 km². This scenario was motivated by the lack of observed lithified carbonate on *Argo II* run A40. Scenario 3 included the entire Dome and the Eastern Block combined, and had an approximate surface area of 130 km². Using the assumptions of a continuous, 1-m thick layer of calcium carbonate and a density of 2.83 g/cm³ for CaCO₃ (average of calcite and aragonite since the precise composition is unknown), the carbon storage was calculated to be 3.1x10¹³ kg, 3.7x10¹³ kg, and 4.4x10¹³ kg of carbon for Scenarios 1, 2, and 3, respectively. Based on our study, the actual carbon storage is likely to be some small fraction of these values. We cannot rule out the presence of lithified carbonate beneath unconsolidated sediments that we observed, so those areas may represent presently preserved carbon (Scenario 1; Scenario 3 if the consolidated carbonate on the Eastern Block preserves the carbon, regardless of eventual seafloor depth). However, we also documented areas on the Dome that are free of unconsolidated sediment where no lithified carbonate was seen. These areas would not contribute to the presently preserved carbon at Atlantis Massif (closer to Scenario 2, for example).

6. Conclusions

The existence of lithified carbonate crust and consolidated carbonate cap features on the Central Dome, Eastern Block, and Western Shoulder of Atlantis Massif can be attributed to the two potential

mechanisms of precipitation and/or sediment cementation previously documented at the LCHF. Both mechanisms rely on the presence of hydrothermal fluid from water-rock interactions occurring during serpentinization in the subsurface. If either (or both) of these mechanisms are the cause of our documented carbonate features, their locations represent seafloor that was linked to subsurface serpentinization by hydrothermal fluid flow.

Acknowledgments

We thank the Data Library and Archives at Woods Hole Oceanographic Institution and the National Deep Submergence Facility for helping us access portions of the *Argo II* and *Alvin* imagery used in this study. We also appreciate the constructive comments provided by three reviewers. This work was conducted while DKB served at the National Science Foundation, associated support is acknowledged. The data compiled and reported in this paper will be archived and openly available in the Marine Geoscience Data System at http://www.marinegeo.org/tools/search/entry.php?id=MAR:30N_Blackman.

References

- Allen, D.E., Seyfried, W.E., 2004. Serpentinization and heat generation: Constraints from Lost City and Rainbow hydrothermal systems, *Geochim. Cosmochim. Acta*, 68(6), 1347–1354, doi:10.1016/j.gca.2003.09.003.
- Alt, J.C., Teagle, A.H., 1999. The uptake of carbon during alteration of ocean crust, *Geochim. Cosmochim. Acta*, 63(10), 1527–1535.
- Andreani, M., Escartín, J., Delacour, A., Ildefonse, B., Godard, M., Dymant, J., Fallick, A.E., Fouquet, Y., 2014. Tectonic structure, lithology, and hydrothermal signature of the Rainbow massif (Mid-Atlantic Ridge 36°14'N), *Geochem., Geophys. Geosyst.*, 15(1), 3543–3571, doi:10.1002/2014GC005269.
- Berner, R.A., 2003. The long-term carbon cycle, fossil fuels and atmospheric composition, *Nature*, 426(November), 323–326, doi:10.1038/nature02131.
- Blackman, D.K., Cann, J.R., Janssen, B., Smith, D.K., 1998. Origin of extensional core complexes: Evidence from the Mid-Atlantic Ridge at Atlantis Fracture Zone, *J. Geophys. Res.*, 103, 21315, doi:10.1029/98JB01756.

- Blackman, D.K., Karson, J.A., Kelley, D.S., Cann, J.R., Früh-Green, G.L., Gee, J.S., Hurst, S.D., John, B.E., Morgan, J., Nooner, S.L., Kent Ross, D., Schroeder, T.J., Williams, E.A., 2002. Geology of the Atlantis Massif (Mid-Atlantic Ridge, 30° N): Implications for the evolution of an ultramafic oceanic core complex, *Mar. Geophys. Res.*, 23, 443–469, doi:10.1023/B:MARI.0000018232.14085.75.
- Blackman, D.K., Ildefonse, B., John, B.E., Ohara, Y., Miller, D.J., MacLeod, C.J., the Expedition 304/305 Scientists, 2006. Proc. IODP, 304/305: College Station TX (Integrated Ocean Drilling Program Management International, Inc.). doi:10.2204/iodp.proc.304305.2006.
- Blackman, D.K., Canales, J.P., Harding, A., 2009. Geophysical signatures of oceanic core complexes, *Geophys. J. Int.*, 178, 593–613, doi:10.1111/j.1365-246X.2009.04184.x.
- Blackman, D.K., Ildefonse, B., John, B.E., Ohara, Y., Miller, D.J., Abe, N., Abratis, M., Andal, E.S., Andreani, M., Awaji, S., Beard, J.S., Brunelli, D., Charney, A.B., Christie, D.M., Collins, J., Delacour, A.G., Delius, H., Drouin, M., Einaudi, F., Escartín, J., Frost, B.R., Früh-Green, G.L., Fryer, P.B., Gee, J.S., Godard, M., Grimes, C.B., Halfpenny, A., Hansen, H.E., Harris, A.C., Tamura, A., Hayman, N.W., Hellebrand, E., Hirose, T., Hirth, J.G., Ishimaru, S., Johnson, K. T.M., Karner, G.D., Linek, M., MacLeod, C. J., Maeda, J., Mason, O.U., McCaig, A.M., Michibayashi, K., Morris, A., Nakagawa, T., Nozaka, T., Rosner, M., Searle, R.C., Suhr, G., Tominaga, M., von der Handt, A., Yamasaki, T., Zhao, X., 2011. Drilling constraints on lithospheric accretion and evolution at Atlantis Massif, Mid-Atlantic Ridge 30N, *J. Geophys. Res. Solid Earth*, 116, 1–25, doi:10.1029/2010JB007931.
- Blackman, D.K., Slagle, A., Guerin, G., Harding, A., 2014. Geophysical signatures of past and present hydration within a young oceanic core complex, *Geophys. Res. Lett.*, 41, 1179–1186, doi 10.1002/2013GL058111.
- Boschi, C., Früh-Green, G.L., Delacour, A., Karson, J.A., Kelley, D.S., 2006. Mass transfer and fluid flow during detachment faulting and development of an oceanic core complex, Atlantis Massif (MAR 30°N), *Geochem., Geophys. Geosyst.*, 7(October 2005), doi:10.1029/2005GC001074.
- Canales, J.P., Tucholke, B.E., Xu, M., Collins, J.A., Duois, D.L., 2008. Seismic evidence for large-scale compositional heterogeneity of oceanic core complexes, *Geochem., Geophys. Geosyst.*, 9(August), doi:10.1029/2008GC002009.
- Cann, J.R., Blackman, D.K., Smith, D.K., McAllister, E., Janssen, B., Mello, S., Avgerinos, E., Pascoe, A.R., Escartín, J., 1997. Corrugated slip surfaces formed at ridge-transform intersections on the Mid-Atlantic Ridge, *Nature*, 385, 329–332. doi:10.1038/385329a0.
- Cannat, M., Sauter, D., Mendel, V., Ruellan, E., Okino, K., Escartín, J., Combier, V., Baala, M., 2006. Modes of seafloor generation at a melt-poor ultraslow-spreading ridge, *Geology*, 34, 605–608, doi:10.1130/G22486.1.
- Coogan, L.A., Gillis, K.M., 2013. Evidence that low-temperature oceanic hydrothermal systems play an important role in the silicate-carbonate weathering cycle and long-term climate regulation, *Geochem., Geophys. Geosyst.*, 14(6), 1771–1786, doi:10.1002/ggge.20113.

- 457 Delacour, A., Früh-Green, G.L., Bernasconi, S.M., Schaeffer, P., Kelley, D.S., 2008a. Carbon
458 geochemistry of serpentinites in the Lost City Hydrothermal System (30°N, MAR), *Geochim.*
459 *Cosmochim. Acta*, 72(15), 3681–3702, doi:10.1016/j.gca.2008.04.039.
- 460 Delacour, A., Früh-Green, G.L., Frank, M., Gutjahr, M., Kelley, D.S., 2008b. Sr- and Nd-isotope
461 geochemistry of the Atlantis Massif (30°N, MAR): Implications for fluid fluxes and lithospheric
462 heterogeneity, *Chem. Geol.*, 254, 19–35, doi:10.1016/j.chemgeo.2008.05.018.
- 463 Dias, Á.S., Früh-Green, G.L., Bernasconi, S.M., Barriga, F.J.A.S., Seahma cruise team, Charles Darwin
464 167 cruise team, 2011. Geochemistry and stable isotope constraints on high-temperature activity
465 from sediment cores of the Saldanha hydrothermal field, *Mar. Geol.*, 279, 128–140,
466 doi:10.1016/j.margeo.2010.10.017.
- 467 Dick, H.J.B., Tivey, M.A., Tucholke, B.E., 2008. Plutonic foundation of a slow-spreading ridge segment:
468 the oceanic core complex at Kane Megamullion, 23°30'N, 45°20'W, *Geochem., Geophys., Geosyst.*,
469 9, Q05014, doi:10.1029/2007GC001645.
- 470 Escartín, J., Smith, D.K., Cann, J., Schouten, H., Langmuir, C.H., Escrig, S., 2008. Central role of
471 detachment faults in accretion of slow-spreading oceanic lithosphere., *Nature*, 455(October), 790–
472 794, doi:10.1038/nature07333.
- 473 Expedition Scientific Party, 2005. Oceanic core complex formation, Atlantis Massif-oceanic core
474 complex formation, Atlantis Massif, Mid-Atlantic Ridge: drilling into the footwall and hanging wall
475 of a tectonic exposure of deep, young oceanic lithosphere to study deformation, alteration, and melt
476 generation. IODP Prel. Rept., 304. doi:10.2204/iodp.pr.304.2005.
- 477 Früh-Green, G.L., Connolly, J.A.D., Plas, A., Kelley, D.S., Grobéty, B., 2004. Serpentinization of
478 Oceanic Peridotites: Implications for Geochemical Cycles and Biological Activity, *Subseafloor*
479 *Biosph. Mid-Ocean Ridges*, 119–136, doi:10.1029/144GM08.
- 480 Früh-Green, G.L., Kelley, D.S., Bernasconi, S.M., Karson, J.A., Ludwig, K.A., Butterfield, D.A., Boschi,
481 C., Proskurowski, G., 2003. 30,000 Years of Hydrothermal Activity at the Lost City Vent Field.,
482 *Science*, 301(July), 495–498, doi:10.1126/science.1085582.
- 483 Goldhammer, R.K., 1997. Compaction and decompaction algorithms for sedimentary carbonates, *J.*
484 *Sediment. Res.* 67, 26–35.
- 485 Grimes, C.B., John, B.E., Cheadle, M.J., Wooden, J.L., 2008. Protracted construction of gabbroic crust at
486 a slow spreading ridge: Constraints from 206Pb/238U zircon ages from Atlantis Massif and IODP
487 Hole U1309D (30°N, MAR), *Geochem., Geophys. Geosyst.*, 9(April), doi:10.1029/2008GC002063.
- 488 Henig, A.S., Blackman, D.K., Harding, A.J., Canales, J.P., Kent, G.M., 2012. Downward continued
489 multichannel seismic refraction analysis of Atlantis Massif oceanic core complex, 30°N, Mid-
490 Atlantic Ridge, *Geochem., Geophys. Geosyst.*, 13(1), 1–25, doi:10.1029/2012GC004059.
- 491 Karson, J.A., 1990. Seafloor spreading on the Mid-Atlantic Ridge: implications for the structure of
492 ophiolites and oceanic lithosphere produced in slow-spreading environments, in Proceedings of
493 Symposium Troodos 1987, pp. 547–553, edited by Malpas, J., *Geological Survey Dept.*, Nicosia.
494
- 495 Karson, J.A., Früh-Green, G.L., Kelley, D.S., Williams, E.A., Yoerger, D.R., Jakuba, M., 2006.

- 496 Detachment shear zone of the Atlantis Massif core complex, Mid-Atlantic Ridge, 30°N, *Geochem.*,
497 *Geophys. Geosyst.*, 7, doi:10.1029/2005GC001109.
- 498 Kelley, D.S., Karson, J.A., Blackman, D.K., Früh-Green, G.L., Butterfield, D.S., Lilley, M.D., Olson, M.
499 D., Schrenk, M.O., Roe, K.K., Lebon, G.T., Rivissigno, P., the AT3-60 Shipboard Party, 2001. An
500 off-axis hydrothermal vent field near the Mid-Atlantic Ridge at 30 degrees N., *Nature*, 412(July),
501 145–149, doi:10.1038/35084000.
- 502 Kelley, D.S., Karson, J.A., Früh-Green, G.L., Yoerger, D.R., Shank, T.M., Butterfield, D.A., Hayes, J.
503 M., Schrenk, M.O., Olson, E.J., Proskurowski, G., Jakuba, M., Bradley, A., Larson, B., Ludwig, K.,
504 Glickson, D., Buckman, K., Bradley, A.S., Brazelton, W.J., Roe, K., Elend, M.J., Delacour, A.,
505 Bernasconi, S.M., Lilley, M.D., Baross, J.A., Summons, R.E., Sylva, S.P., 2005. A Serpentine-
506 Hosted Ecosystem: The Lost City Hydrothermal Field, *Science*, 307(March), 1428–1434,
507 doi:10.1126/science.1102556.
- 508 Lowell, R.P., Rona, P.A., 2002. Seafloor hydrothermal systems driven by the serpentinization of
509 peridotite, *Geophys. Res. Lett.*, 29(11), 1–4.
- 510 Ludwig, K.A., Kelley, D.S., Butterfield, D.A., Nelson, B.K., Früh-Green, G.L., 2006. Formation and
511 evolution of carbonate chimneys at the Lost City Hydrothermal Field, *Geochim. Cosmochim. Acta*,
512 70, 3625–3645, doi:10.1016/j.gca.2006.04.016.
- 513 Ludwig, K.A., Shen, C.C., Kelley, D.S., Cheng, H., Edwards R.L., 2011. U-Th systematics and ²³⁰Th
514 ages of carbonate chimneys at the Lost City Hydrothermal Field, *Geochim. Cosmochim. Acta*, 75(7),
515 1869–1888, doi:10.1016/j.gca.2011.01.008.
- 516 MacLeod, C.J., Searle, R.C., Murton, B.J., Casey, J.F., Mallows, C., Unsworth, S.C., Achenbach, K.L.,
517 Harris, M., 2009. Life cycle of oceanic core complexes, *Earth Planet. Sci. Lett.*, 287, 333–344,
518 doi:10.1016/j.epsl.2009.08.016.
- 519 MacLeod, C.J., Carlut, J., Escartín, J., Horen, H., Morris, A., 2011. Quantitative constraint on footwall
520 rotations at the 15°45'N oceanic core complex, Mid-Atlantic Ridge: Implications for oceanic
521 detachment fault processes, *Geochem., Geophys. Geosyst.*, 12(5), 1–29,
522 doi:10.1029/2011GC003503.
- 523 Mallows, C., Searle, R.C., 2012. A geophysical study of oceanic core complexes and surrounding terrain,
524 Mid-Atlantic Ridge 13°N–14°N, *Geochem., Geophys. Geosyst.*, 13(1), 1–27,
525 doi:10.1029/2012GC004075.
- 526 McCaig, A.M., Cliff, R.A., Escartín, J., Fallick, A.E., MacLeod, C.J., 2007. Oceanic detachment faults
527 focus very large volumes of black smoker fluids, *Geology*, 35(10), 935–938,
528 doi:10.1130/G23657A.1.
- 529 McCaig, A.M., Delacour, A., Fallick, A.E., Castelain, T., Früh-Green, G.L., 2010. Detachment fault
530 control on hydrothermal circulation systems: Interpreting the subsurface beneath the TAG
531 hydrothermal field using the isotopic and geological evolution of oceanic core complexes in the
532 Atlantic, *Geophys. Monogr. Ser.*, 188, 207–239, doi:10.1029/2008GM000729.
- 533 Morris, A., Gee, J.S., Pressling, N., John, B.E., MacLeod, C.J., Grimes, C.B., Searle, R.C., 2009.
534 Footwall rotation in an oceanic core complex quantified using reoriented Integrated Ocean Drilling

- 535 Program core samples, *Earth Planet. Sci. Lett.*, 287, 217–228, doi:10.1016/j.epsl. 2009.08.007.
- 536 Pariso, J.E., Rommevaux, C., Sempere, J.-C., 1996. Three-dimensional inversion of marine magnetic
537 anomalies: Implications for crustal accretion along the Mid-Atlantic Ridge (28°-31°30' N), *Mar.*
538 *Geophys. Res.*, 18, 85–101, doi:10.1007/BF00286204.
- 539 Schroeder, T., John, B., Frost, B.R., 2002. Geologic implications of seawater circulation through
540 peridotite exposed at slow-spreading mid-ocean ridges, *Geology*, 30(4), 367–370.
- 541 Schroeder, T., John, B.E., 2004. Strain localization on an oceanic detachment fault system, Atlantis
542 Massif, 30°N, Mid-Atlantic Ridge, *Geochem. Geophys. Geosyst.*, 5, Q11007,
543 doi:10.1029/2004GC000728.
- 544 Smith, D.K., Cann, J.R., Escartín, J., 2006. Widespread active detachment faulting and core complex
545 formation near 13 degrees N on the Mid- Atlantic Ridge, *Nature*, 442, 440–443,
546 doi:10.1038/nature04950.
- 547 Snyder, G., Poreda, R., Hunt, A., Fehn, U., 2001. Regional variations in volatile composition: Isotopic
548 evidence for carbonate recycling in the Central American volcanic arc, *Geochem. Geophys. Geosyst.*, 2,
549 2001GC000163.
- 550 Sun, X., Turchyn, A.V., 2014. Significant contribution of authigenic carbonate to marine carbon burial,
551 *Nat. Geosci.*, 8(1), 201–204, doi:10.1038/ngeo2070.
- 552 Tucholke, B.E., 1986. Structure of basement and distribution of sediments in the western North Atlantic
553 Ocean, in: The western North Atlantic region, The geology of North America, vol. M. Vogt, P. R.,
554 Tucholke, B. E. (Eds.), *Geol. Soc. Am.*, Boulder, Colo., pp. 331-340.
- 555 Tucholke, B.E., Lin, J., Kleinrock, M.C., 1998. Megamullions and mullion structure defining oceanic
556 metamorphic core complexes on the Mid-Atlantic ridge, *J. Geophys. Res.*, 103, 9857–9866,
557 doi:10.1029/98JB00167.
- 558 Tucholke, B.E., Fujioka, K., Ishihara, T., Hirth, G., Kinoshita, M., 2001. Submersible study of an oceanic
559 megamullion in the central North Atlantic, *J. Geophys. Res.*, 106, 16145,
560 doi:10.1029/2001JB000373.
- 561 Tucholke, B.E., Humphris, S.E., Dick, H.J.B., 2013. Cemented mounds and hydrothermal sediments on
562 the detachment surface at Kane Megamullion: A new manifestation of hydrothermal venting,
563 *Geochem., Geophys. Geosyst.*, 14(9), 3352–3378, doi:10.1002/ggge.20186.
- 564 Weaver, P.P.E., Rothwell, R.G., 1987. Sedimentation on the Madeira Abtssal Plain over the last 300000
565 years, *Geol. Soc. London Spec. Publ.*, 31, 71-86, doi: 10.1144/GSL.SP.1987.031.01.07.
- 566
- 567 Wessel, P., Smith, W.H.F., 1991. Free software helps map and display data, *Eos Trans. AGU*, 72, 441,
568 445-446.
- 569
- 570
- 571

572 Table

573

Table 1. Coordinates and Photo Timestamps for Identified Lithified Carbonate Crust Locations on the Central Dome and Western Shoulder.

Central Dome- November 21/22, 2000			Central Dome- November 21/22, 2000 Cont.		
<i>Photo Timestamp</i>	<i>Latitude</i>	<i>Longitude</i>	<i>Photo Timestamp</i>	<i>Latitude</i>	<i>Longitude</i>
21:54:03	30.171453	-42.126776	03:01:43	30.172213	-42.120684
22:02:43	30.171426	-42.126948	03:04:23	30.172282	-42.120326
22:10:23	30.171359	-42.127420	03:10:03	30.172406	-42.119498
22:26:43	30.170973	-42.128776	03:16:23	30.172558	-42.118607
22:32:03	30.170879	-42.129503	03:32:23	30.173023	-42.116169
22:56:43	30.169788	-42.129432	03:37:23	30.173183	-42.115392
23:11:43	30.168656	-42.128215	03:38:03	30.173207	-42.115293
23:23:43	30.167714	-42.127177	03:51:03	30.173538	-42.113397
23:44:43	30.169079	-42.126997	04:00:03	30.173923	-42.112863
23:52:03	30.169971	-42.126964	04:07:23	30.174392	-42.112574
23:56:43	30.170581	-42.126932	04:56:23	30.174552	-42.112511
00:05:23	30.171744	-42.126919	05:26:03	30.173286	-42.112143
00:48:23	30.173071	-42.124973	05:38:23	30.173781	-42.111864
00:51:03	30.172933	-42.124679	05:43:43	30.174129	-42.111751
00:55:03	30.172700	-42.124295	05:47:23	30.174384	-42.111654
01:19:23	30.171027	-42.121435	05:55:43	30.174973	-42.111429
01:42:03	30.169972	-42.120915	05:59:43	30.175124	-42.111350
02:14:23	30.173356	-42.118388	06:12:43	30.174868	-42.110781
02:16:43	30.173585	-42.118288	06:31:23	30.174296	-42.109203
02:20:03	30.173726	-42.118492	Western Shoulder- November 23/24, 2000		
02:21:23	30.173681	-42.118652	22:31:25	30.121721	-42.174281
02:27:43	30.173433	-42.119394	23:24:10	30.120280	-42.172299
02:41:03	30.172465	-42.121074	00:45:56	30.124359	-42.166933
02:47:03	30.172023	-42.121738	03:20:31	30.129243	-42.167987
02:53:23	30.172004	-42.121611	04:38:34	30.127243	-42.173117

Figure Captions

Figure 1. Bathymetry map of Atlantis Massif. Black solid lines indicate plate boundary. Grey depth contours at 500 m interval. Black circle denotes location of IODP Hole U1309D on the Central Dome. Inset shows location in the central Atlantic.

Figure 2. *Argo II* tracklines and observed geology along each track: (A) Lithified carbonate crust distribution on the massif (gray diamonds) identified by *Argo II* mosaics and *Alvin* samples. No lithified carbonate crust was distinguished on *Argo II* track A40. Black circles denote drilling during IODP Expedition 304/305; (B) Lithified carbonate crust distribution for *Argo II* track A39 and *Alvin* samples. IODP holes labeled; (C) Lithified carbonate crust distribution for *Argo II* track A41.

Figure 3. Photo mosaic and interpreted seafloor morphological groups on the Central Dome. Annotated (A1, B1) and corresponding original (A2, B2) mosaics are from *Argo II* track A39, displaying lithified carbonate crust (“pancake shaped” feature morphological group; annotated-white), debris (annotated-grey), and unconsolidated sediment (pelagic ooze; annotated-black lines denoting ripple orientation). Field of view ranges from 2-4 m in width and 5-8 m (A) or 9-12 m (B) in length.

Figure 4. Photo mosaic from *Argo II* track A40 in the Central Dome, indicating possible morphologic association with seafloor type: (A) Exposed rock and debris with some non-igneous drape or alteration and unconsolidated sediment (pelagic ooze) on the surface; (B) Exposed rock and debris dusted with unconsolidated sediment (pelagic ooze) from near the peak of track A40; (C) Transition between debris patch and unconsolidated sediment (pelagic ooze) patch downslope from the peak. The large frame in each of these photomosaics is ~3 m x 2 m in size; lengths range from ~7-10 m.

Figure 5. Images from the Eastern Block displaying a scarp of fractured pillow basalts topped by a consolidated, laminated carbonate cap (“cliff cap” morphological group) with an overlying dusting of unconsolidated sediment (pelagic ooze): (A, B) *Alvin* dive 3644 images; (C) *Argo II* track A43 mosaic. Fields of view are ~2-3 m wide by 2-5 m high.

Figure 6. Photo mosaic and interpreted seafloor morphological groups in the Western Shoulder. Annotated (A1, B1) and corresponding original (A2, B2) mosaics from *Argo II* A41 displaying lithified carbonate crust (“pancake shaped” feature morphological group; annotated-white), rounded pillow basalt debris (annotated-grey), and unconsolidated sediment (pelagic ooze; annotated-black lines denoting ripple orientation). Photomosaics are 2-3 m wide by ~7-11 m long.

Figure 7. Seafloor slope angle and carbonate locations map (bottom) with 3D bathymetry map (top) for spatial comparison.

616
617 Figure 1

Figure 2A

Figure 2B

623
624 Figure 2C

625
626 Figure 3

627
628 Figure 4

629
630
631 Figure 5

632 Figure 6
633

Figure 7