



PEARL

**Magmatism, serpentinization and life: Insights through drilling the Atlantis Massif (IODP Expedition 357)**

Fruh-Green, G; Orcutt, Beth N.; Roumejon, S; Lilley, Marvin D.; Morono, Yuki; Cotterill, Carol; Green, Sophie; Escartin, Javier; John, Barbara E.; McCaig, Andrew M.; Cannat, Mathilde; Menez, B; Schwarzenbach, Esther M.; Williams, Morgan J.; Morgan, Sally; Lang, Susan Q.; Shrenk, M; Brazelton, William J.; Akizawa, Norikatsu; Boschi, Chiara; Dunkel, Kristina G.; Quéménéurr, M; Whattam, Scott A.; Mayhew, Lisa; Harris, Michelle; Bayrakci, Gaye; Behrmann, Jan Hinrich; Herro-Bervera, E; Hesse, Kirsten; Liu, Hai Quan; Ratnayake, Amila Sandaruwan; Twing, Katrina; Weis, Dominique; Zhao, Rui; Bilenker, Laura

**Published in:**

Lithos

**DOI:**

[10.1016/j.lithos.2018.09.012](https://doi.org/10.1016/j.lithos.2018.09.012)

**Publication date:**

2018

**Link:**

[Link to publication in PEARL](#)

**Citation for published version (APA):**

Fruh-Green, G., Orcutt, B. N., Roumejon, S., Lilley, M. D., Morono, Y., Cotterill, C., Green, S., Escartin, J., John, B. E., McCaig, A. M., Cannat, M., Menez, B., Schwarzenbach, E. M., Williams, M. J., Morgan, S., Lang, S. Q., Shrenk, M., Brazelton, W. J., Akizawa, N., ... Bilenker, L. (2018). Magmatism, serpentinization and life: Insights through drilling the Atlantis Massif (IODP Expedition 357). *Lithos*, 323(0), 137-155.  
<https://doi.org/10.1016/j.lithos.2018.09.012>

"This is an accepted manuscript of an article published by Elsevier in *Lithos* 2018 available at:

<https://www.sciencedirect.com/science/article/pii/S0024493718303335>"

Please cite this article as: Früh-Green, G., Orcutt, B., Rouméjon, S., Lilley, M., Morono, Y., Cotterill, C., Green, S., Escartin, J., John, B.E., McCaig, A.M., Cannat, M., Ménez, B., Schwarzenbach, E.M., Williams, M., Morgan, S., Lang, S.Q., Schrenk, M.O., Brazelton, W.J., Akizawa, N., Boschi, C., Dunkel, K.G., Quéméneur, M., Whattam, S., Mayhew, L., Harris, M., Bayrakci, G., Behrmann, J., Herrero-Bervera, E., Hesse, K., Liu, H., Ratnayake, A.S., Twing, K., Weis, D., Zhao, R., Bilenker, L. "Magmatism, serpentinization and life: Insights through drilling the Atlantis Massif (IODP Expedition 357)" *Lithos* in press

1 **Magmatism, serpentinization and life: Insights through drilling the Atlantis Massif (IODP**  
2 **Expedition 357)**

3  
4 Gretchen L. Früh-Green<sup>a,\*</sup>, Beth N. Orcutt<sup>b</sup>, Stéphane Rouméjon<sup>a</sup>, Marvin D. Lilley<sup>c</sup>, Yuki  
5 Morono<sup>d</sup>, Carol Cotterill<sup>e</sup>, Sophie Green<sup>e</sup>, Javier Escartin<sup>f</sup>, Barbara E. John<sup>g</sup>, Andrew M.  
6 McCaig<sup>h</sup>, Mathilde Cannat<sup>f</sup>, Bénédicte Ménez<sup>f</sup>, Esther M. Schwarzenbach<sup>i</sup>, Morgan J.  
7 Williams<sup>j,1</sup>, Sally Morgan<sup>k</sup>, Susan Q. Lang<sup>l</sup>, Matthew O. Schrenk<sup>m</sup>, William J. Brazelton<sup>n</sup>,  
8 Norikatsu Akizawa<sup>o,2</sup>, Chiara Boschi<sup>p</sup>, Kristina G. Dunkel<sup>q</sup>, Marianne Quéméneur<sup>f</sup>, Scott A.  
9 Whattam<sup>s,3</sup>, Lisa Mayhew<sup>t</sup>, Michelle Harris<sup>u,4</sup>, Gaye Bayrakci<sup>u</sup>, Jan-Hinrich Behrmann<sup>v</sup>, Emilio  
10 Herrero-Bervera<sup>w</sup>, Kirsten Hesse<sup>x</sup>, Hai-Quan Liu<sup>y</sup>, Amila Sandaruwan Ratnayake<sup>z,5</sup>, Katrina  
11 Twing<sup>m,n</sup>, Dominique Weis<sup>aa</sup>, Rui Zhao<sup>ab</sup>, Laura Bilenker<sup>aa</sup>

12  
13  
14 <sup>a</sup> Institute of Geochemistry and Petrology, ETH Zurich, Clausiusstrasse 25, 8092 Zürich,  
15 Switzerland

16 <sup>b</sup> Bigelow Laboratory for Ocean Sciences, East Boothbay, ME, USA

17 <sup>c</sup> University of Washington, School of Oceanography, Seattle WA 98195, USA

18 <sup>d</sup> Japan Agency for Marine-Earth Science and Technology, Kochi Institute for Core Sample  
19 Research, Kochi, Japan

20 <sup>e</sup> ECORD Science Operator, British Geological Survey, Edinburgh EH14 4AP, UK

21 <sup>f</sup> Institut de Physique du Globe de Paris, CNRS, 1 rue Jussieu, 75238 Paris cedex 05, France

22 <sup>g</sup> University of Wyoming, Laramie WY 82071, USA

23 <sup>h</sup> University of Leeds, School of Earth and Environment, Leeds LS2 9JT, United Kingdom

24 <sup>l</sup> Institute of Geological Sciences, Freie Universität Berlin, Malteserstrasse 74-100, 12249 Berlin,  
25 Germany

26 <sup>j</sup> The Australian National University, Department Research School of Earth Sciences, Mills Rd,  
27 Acton, Australia. <sup>1</sup>Present address: CSIRO Mineral Resources, 26 Dick Perry Avenue,  
28 Kensington WA 6151, Australia

29 <sup>k</sup> ECORD Science Operator, Department of Geology, University of Leicester, University Road,  
30 Leicester LE1 7RH, United Kingdom

31 <sup>1</sup> University of South Carolina, 701 Sumter St. EWS 617, Columbia SC 29208, USA

32 <sup>m</sup> Michigan State University, 288 Farm Lane, East Lansing MI 48824, USA

33 <sup>n</sup> University of Utah, 257 South 1400 East, Salt Lake City, UT 84112-0840, USA

34 <sup>o</sup> Kanazawa University, Department of Earth Sciences, Kakuma Kanazawa, Ishikawa 920-1192  
35 JAPAN. <sup>2</sup>Present address: Atmosphere and Ocean Research Institute, The University of Tokyo  
36 5-1-5, Kashiwanoha, Kashiwa, Chiba 277-8564 Japan

37 <sup>p</sup> Institute of Geosciences and Earth Resources – CNR, Via Moruzzi 1, 56124 Pisa, Italy

38 <sup>q</sup> Physics of Geological Processes, University of Oslo, Sem Sælands vei 24, 0371 Oslo, Norway

39 <sup>r</sup> Mediterranean Institute of Oceanography (MIO), Aix Marseille Univ., Université de Toulon,  
40 CNRS, IRD, MIO UM 110, 13288, Marseille, France

41 <sup>s</sup> Korea University, Department Earth and Environmental Sciences, Seoul 136-701, Republic of  
42 Korea. Present address: Department of Geosciences, King Fahd University of Petroleum and  
43 Minerals, Dhahran 31261, Saudi Arabia

44 <sup>t</sup> University of Colorado – Boulder, 2200 Colorado Ave., Boulder CO 80466, USA

45 <sup>u</sup> University of Southampton, National Oceanography Centre, European Way, Southampton,  
46 SO14 3ZH, United Kingdom. <sup>4</sup> Present address: School of Geography, Earth and  
47 Environmental Sciences, 109 Fitzroy Building, Plymouth University, Plymouth PL4 8AA,  
48 United Kingdom

49 <sup>v</sup> GEOMAR Helmholtz Centre for Ocean Research Kiel, Wischhofstr. 1-3, 24148 Kiel, Germany

50 <sup>w</sup> University of Hawaii at Manoa, SOEST-Hawaii Institute of Geophysics and Planetology, 1680  
51 East West Road, Honolulu 96822, USA

52 <sup>x</sup> GeoZentrum Nordbayern, Friedrich-Alexander-University Erlangen-Nuremberg, Schlossgarten  
53 5a, 91054 Erlangen, Germany

54 <sup>y</sup> Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Key Laboratory of  
55 Marginal Sea Geology, 511 Kehua Street, Tianhe, Guangzhou 510640, China

56 <sup>z</sup> Shimane University, Faculty of Science and Engineering, 1060 Nishikawatsu Matsue, Shimane  
57 690-8504, Japan. <sup>5</sup>Present address: Mineral Resources and Technology, Faculty of Science and  
58 Technology, Uva Wellassa University, Passara Road, Badulla 90000, Sri Lanka

59 <sup>aa</sup> University of British Columbia, Earth, Ocean and Atmospheric Sciences, 2020-2207 Main  
60 Mall, Vancouver, BC V6T-1Z4, Canada

61 <sup>ab</sup> Centre for Geobiology, University of Bergen, Allegaten 4, 5007 Bergen, Norway

62

63

64 \*Corresponding author: Gretchen L. Früh-Green at Institute of Geochemistry and Petrology,  
65 ETH Zurich, Clausiusstrasse 25, 8092 Zürich, Switzerland. Email address: frueh-  
66 green@erdw.ethz.ch

67

68 **Keywords:** IODP Expedition 357, Atlantis Massif, detachment faulting, serpentinization, Si  
69 metasomatism, deep biosphere

## 70 **1. Introduction**

71 It is now well recognized that slow spreading ridges are formed by interlinked processes of  
72 magmatism, asymmetric extension, and detachment faulting that result in the exposure and  
73 alteration of lower crustal and mantle-derived rocks in oceanic core complexes (OCCs)  
74 (Andreani et al., 2007; Boschi et al., 2006; Cannat, 1993; Früh-Green et al., 2004; Karson et al.,  
75 2006; Kelemen et al., 2007; Rouméjon et al, 2015). OCCs contain olivine-rich rocks that interact  
76 with seawater to produce serpentinite over a range of temperatures (Andreani et al., 2007; Boschi  
77 et al., 2006a; Boschi et al., 2006b; Cannat, 1993; Früh-Green et al., 2004; Karson et al., 2006;  
78 Kelemen et al., 2007; Rouméjon et al, 2015). Serpentinization is a fundamental process that  
79 controls rheologic and geophysical properties (Escartin et al, 2008; Schroeder et al, 2002) and is  
80 associated with the uptake or release of many major and minor components (Alt and Shanks,  
81 2003; Boschi et al., 2008; Delacour et al., 2008; Früh-Green et al., 2004; Schwarzenbach et al.,  
82 2012). Serpentinization reactions also lead to highly reduced, alkaline (pH 9-12) fluids with high  
83 concentrations of hydrogen, methane and formate, and which have important consequences for  
84 long-term global geochemical fluxes and for biogeochemical cycles (Holm and Charlou, 2001;  
85 Konn et al., 2009; Lang et al., 2018; Proskurowski et al., 2006, 2008).

86  
87 The Atlantis Massif (30°N, Mid-Atlantic Ridge) is one of the best-studied OCCs and hosts the  
88 off-axis Lost City hydrothermal field (LCHF) on its southern wall (Fig. 1). Serpentinization  
89 reactions in the underlying mantle rocks produce high pH (9-11), <91°C fluids that form large  
90 carbonate-brucite structures upon venting on the seafloor (Kelley et al., 2001, 2005; Ludwig, et  
91 al., 2006). The fluids have high concentrations of H<sub>2</sub>, CH<sub>4</sub>, C<sub>2</sub>+ alkanes and formate (HCOO<sup>-</sup>)  
92 that support novel microbial communities dominated by CH<sub>4</sub>-cycling archaea in the

93 hydrothermal carbonate deposits (Brazelton et al., 2006; Brazelton and Baross, 2009; Lang et al.,  
94 2010; Méhay et al., 2013; Proskurowski et al., 2006, 2008; Schrenk et al., 2004). Formate and  
95 low molecular weight hydrocarbons in the Lost City hydrothermal vents are believed to be  
96 formed by abiogenic processes during serpentinization at depth (Lang et al., 2012, 2018;  
97 Proskurowski et al., 2008). Thus, the Atlantis Massif provides a natural laboratory to study the  
98 links between serpentinization processes and microbial activity in the shallow subsurface of  
99 ultramafic and mafic rock sequences that have been uplifted to the seafloor along a major  
100 detachment fault zone (Blackman et al., 2002; Cann et al., 1997; Boschi et al., 2006; Karson et  
101 al., 2006; Kelley et al., 2001, 2005; Schroeder and John, 2004). The processes controlling fluid  
102 flow and a deep biosphere are intimately linked; however, the spatial scale of lithologic  
103 variability, the implications for fluid flow paths and geochemical exchange, and the  
104 consequences for subsurface ecosystems supported by these systems remain poorly constrained.  
105  
106 Here we present an overview of Expedition 357 of the International Ocean Discovery Program  
107 (IODP), which cored seventeen shallow holes at nine sites (Figs. 1, 2) across the Atlantis Massif  
108 (Früh-Green et al, 2016). Expedition 357 was implemented by the ECORD Science Operator  
109 (ESO) as a Mission Specific Platform (MSP) expedition and consisted of an offshore phase on  
110 board the *RRS James Cook* in fall 2015 and a two-week onshore phase at the IODP Bremen Core  
111 Repository in January-February 2016 (Früh-Green et al., 2017a). A major aim of drilling was to  
112 investigate seawater infiltration and alteration processes, and their influence on the nature and  
113 distribution of microbial communities in lithologically heterogeneous domains of an oceanic  
114 core complex. Drilling along a spreading-parallel, east-west profile with seven sites targeted the  
115 serpentinite basement at varying distances away from the ridge axis and the Lost City vent field

116 (Fig. 1, Table 1; see also Früh-Green et al., 2015). Two sites were drilled on the eastern part of  
117 the southern wall (Sites M0068 and M0075), three sites in the central section north of Lost City  
118 (Sites M0069, M0072, and M0076), and two sites on the western end (Sites M0071 and M0073,  
119 with no recovery at M0073). This 8.5 km long profile allows us to explore the extent and activity  
120 of the subsurface biosphere in an actively serpentinizing environment and assess how abiotic and  
121 biotic processes change with aging of the lithosphere, variations in rock type, and with time of  
122 exposure on the seafloor. Two further shallow sites towards the central dome of the massif (Sites  
123 M0070 and M0074) targeted the mafic, plutonic domain drilled at IODP Site U1309. Penetration  
124 and core recovery were limited at these northern sites, and the recovered sequences were  
125 dominated by carbonate sediments and sedimentary breccias. The cores obtained during IODP  
126 Expedition 357 are the first continuous sequences of fault rocks recovered along a major  
127 detachment fault that has an inferred thickness of ~100 m (e.g., Karson et al., 2006; Schroeder  
128 and John, 2004). These cores provide a unique opportunity to study the interaction of  
129 magmatism, deformation and fluid-rock interaction during the evolution of the Atlantis Massif  
130 and the impact these processes on habitability for microorganisms.

131

## 132 **2. Expedition strategy and methods**

133 To obtain a comprehensive view of active serpentinization, fluid circulation and microbial  
134 activity, a strategy was developed based on the use of seabed drills that combined coring with  
135 water sampling and *in situ* geochemical measurements during drilling (Früh-Green et al., 2015).  
136 To enable continuous operations, two seabed drills were used: the British Geological Survey  
137 (BGS) RockDrill2 (RD2) and the Meeresboden-Bohrgerät 70 (MeBo) from the Center for  
138 Marine Environmental Sciences (MARUM; University of Bremen, Germany). This was the first



139 time that seabed drill technology was used in the ocean drilling program. Both drills are remotely  
140 operated systems that are lowered onto the seabed, with power and control maintained from the  
141 ship via an umbilical and using multiple rods and core barrels to progressively penetrate into the  
142 seabed (Früh-Green et al., 2017b). They are both based on an HQ-size, diamond coring system,  
143 producing between 61 and 62 mm diameter cores, similar in size to the standard IODP core  
144 diameter, while cutting a smaller diameter hole. By sitting on the seabed, they do not require  
145 heave compensation and consequently have good control on bit weight, analogous to land-based  
146 coring, and bottom seawater is used as the drilling fluid.

147  
148 The expedition included engineering developments that allowed continuous measurement of  
149 geochemical parameters during drilling, sampling of bottom water after drilling, and the injection  
150 of synthetic contamination tracers during drilling. To evaluate the composition of fluids  
151 emanating from the flushed boreholes in real-time, a suite of *in situ* sensors mounted on the drills  
152 measured dissolved oxygen, hydrogen and methane, temperature, pH, and oxidation-reduction  
153 potential (ORP) during coring operations. Bottom water was collected prior to drilling using the  
154 ship's CTD Niskin bottle rosette and after drilling using Niskin bottles mounted on the drills.  
155 Each rock drill was also equipped with a pump system to deliver perfluoromethylcyclohexane  
156 (PFC) tracer during drilling to assess seawater contamination of the cores (Orcutt et al., 2017).  
157 Shipboard sampling also evaluated contamination potential of the drilling equipment itself,  
158 including greases and other lubricants. When recovered to deck, water samples were  
159 immediately collected for dissolved H<sub>2</sub> and CH<sub>4</sub> concentration analyses, cell counts and PFC  
160 tracer, which were measured onboard, and subsamples were taken for shore-based geochemical  
161 and microbiological analyses (see Früh-Green et al., 2017b). Borehole plug systems were also

162 designed to enable future sampling of borehole fluids; these were installed at Holes M0072B and  
163 M0075B (Früh-Green et al., 2017b). These will be visited on a US-led research expedition in  
164 September 2018 with the ROV *Jason* (funded by the National Science Foundation) to further  
165 investigate the serpentinization and microbiological processes operating in this system.

166

167 To accomplish the microbiology related objectives of the expedition and to enable preservation  
168 of ephemeral microbiological properties, whole round core (WRC) samples were collected  
169 shipboard immediately after core retrieval, curation, and scanning with the multi-sensor core  
170 logger. In total, 42 WRC samples were taken from the 17 holes drilled during the offshore phase  
171 of the expedition, yielding nearly 8 m in total length and representing ~14% of the entire core  
172 recovered. For part of these WRCs, potentially contaminated exterior surfaces were flame-  
173 sterilized on the ship in a KOACH open clean system with care to avoid potential contaminants  
174 (e.g. dust). Interior pieces of rock were collected after crushing using a flame-sterilized chisel  
175 and fixed for microbial cell detection (Früh-Green et al., 2017b). Subsamples of WRCs were  
176 used to establish 29 different enrichment experiments on the ship, with initial indications of  
177 positive activity in some of the treatments based on elevated cell counts. Remaining portions of  
178 the WRCs were immediately frozen at -80°C and shipped to the Kochi Core Center, Japan, at the  
179 end of the offshore phase. There, exteriors of the WRCs were removed under sterile conditions  
180 with a band saw system equipped in a clean booth (Orcutt et al., 2017) and the WRC interiors  
181 and exteriors were subsampled for multiple shore-based analyses.

182

183 Taking advantage of weather and operational downtime, IODP Expedition 357 generated a high-  
184 resolution multibeam bathymetry map across the Atlantis Massif. The new bathymetry, after

185 processing, provides a grid with a resolution of 20–50 m, which is two to five times higher  
186 resolution than previously available bathymetry for this area (100 m) (Blackman et al., 2002).  
187 The survey covered the entire striated detachment fault surface of the Atlantis Massif and  
188 surrounding terrain, which included the ridge axis to the east, the Atlantis Fracture Zone to the  
189 south, the tectonized terrain off-axis and west of the detachment, and its gradual narrowing  
190 transition to the adjacent seafloor to the north (Fig. 1).

191  
192 As with all IODP mission-specific platform expeditions, no cores were split during the offshore  
193 phase. A comprehensive onshore phase at the IODP Bremen Core Repository complemented the  
194 offshore phase, during which the cores were described in detail and the IODP minimum and  
195 some standard measurements were made (see Früh-Green et al., 2017b for details). Bulk rock  
196 preparation and geochemical analyses deviated from standard IODP procedure and were  
197 conducted in the ultraclean laboratories of the Pacific Centre for Isotopic and Geochemical  
198 Research at the University of British Columbia (Canada). Major elements were measured using  
199 an inductively coupled plasma-optical emission spectrometer (ICP-OES) and trace elements  
200 (including Cr and Ni) were determined with a high-resolution inductively coupled plasma-mass  
201 spectrometer (HR-ICP-MS), using international standards and an in-house standard (see  
202 Geochemistry section in Früh-Green et al., 2017b).

203

### 204 **3. Expedition highlights**

205 In brief, comparison of the recovered rock types (Fig. 2), cross-cutting relationships and the  
206 newly produced bathymetric map (Fig. 1) indicate that the central sites recovered *in situ*  
207 sequences that provide a record of (from oldest to youngest): early magmatism emplaced in the  
208 shallow mantle, multiphase progressive seawater penetration, serpentinization and  
209 metasomatism, dolerite intrusions, and recent basaltic volcanism. As the boreholes were located  
210 across the detachment fault zone, the cores likely sampled different structural levels which were  
211 tectonically transposed over the thickness of the detachment fault zone (~100 m). The two  
212 eastern Sites M0075 and M0068 and the western Site M0071 recovered fault scarp deposits. The  
213 scarp deposits and rubble intervals provide no information as to the orientation of structures or  
214 veins; however, the rock types, deformation and alteration characteristics, as well as contact  
215 relationships preserved in coherent portions of the cores, are similar to those recovered in the *in*  
216 *situ* sequences at the central sites and provide information about the magmatic, metamorphic and  
217 deformation history at shallow levels of the detachment fault zone. Sedimentary breccias with  
218 variably rounded clasts (predominantly basalt with some serpentinite, gabbro, and dolerite) in a  
219 foraminiferous carbonate matrix were recovered at Site M0070 to the north of the east-west  
220 transect, and only one short highly disturbed sediment core was recovered from Site M0074.

221

#### 222 *3.1 Multibeam bathymetry*

223 New bathymetric mapping revealed a striated detachment surface with variations in geometry  
224 along-axis from south to north (Fig. 1a). Near the transform wall, the detachment fault surface  
225 summits near the Lost City hydrothermal field at <800 meters below sea level (mbsl); from there  
226 it dips ~8° east toward the ridge axis, ~6° to the west, and ~8°–10° to the north toward the

227 central dome. The detachment deepens to the north to >1500 mbsl. This deepening is associated  
228 with a change in shape; the detachment shows curvature along the spreading direction with  
229 slopes of up to 15° at its termination toward the ridge axis, becomes subhorizontal, and dips up  
230 to 10° away from the axis.

231  
232 The hanging wall cutoff (termination) is well preserved toward the northern, deeper part of  
233 Atlantis Massif, corresponding to a sharp contact between the ridgeward-dipping striated fault  
234 plane and the adjacent seafloor volcanic terrain. This volcanic terrain has a <10° tilt westward,  
235 away from the ridge axis, and hosts volcanic cones and a bathymetric texture typical of volcanic  
236 terrain along the rift valley floor (Fig. 1b). This portion of volcanic seafloor is bound further east  
237 by a fault scarp and corresponds to the top of a back-tilted tectonic block, as previously  
238 identified (Blackman et al., 2002; Cann et al., 1997).

239  
240 The termination is not preserved to the south, ridgeward of the elevated portion of the  
241 detachment. Instead, the striated surface is dissected by a major scarp, with a relief of up to 3000  
242 m from the rift valley floor and the top of the scarp. This scarp shows a lobate structure  
243 indicating mass-wasting processes (slumping). Laterally, it links north with the fault scarp  
244 bounding the tectonically uplifted volcanic seafloor, which corresponds to the present-day rift  
245 valley wall fault. The striated surface is also affected by extensive mass wasting along its  
246 southern boundary toward the transform valley (Fig. 1b). The mass wasting produces scarps that  
247 are concave at their subvertical headwall. The transform wall south of Atlantis Massif has an  
248 average slope of ~20° and numerous channels bound by high ridges channelling debris at the  
249 base of the transform valley. Widespread mass wasting at smaller scales is also observed on

250 steeper slopes of the detachment fault surface along the flanks of larger-scale striations. Late  
251 small-slip faults (centimeters to tens of meters) cut the striated detachment surface and are  
252 subparallel to oblique to the ridge axis. Most have scarps facing away from the ridge axis, with  
253 scarps up to ~10–20 m in vertical relief and which have irregular traces.

254

## 255 *3.2 Lithology, alteration, and structure*

### 256 *3.2.1. Lithology*

257 More than 57 m of core were recovered, with borehole penetration depths ranging from 1.3 to  
258 16.44 meters below seafloor (mbsf). Core recoveries ranged from 23 to 75% of total penetration,  
259 with 100% recovery in some intervals (Table 1; Figure 2). This significant recovery of exhumed  
260 mantle peridotite at the surface of a major detachment fault zone is unprecedented in the history  
261 of ocean drilling and provides a new window into understanding interlinked processes of crustal  
262 accretion, deformation and alteration that to date could not be deduced with conventional rotary  
263 drilling, dredging or submersible sampling. Many lithologic and intrusive contacts, deformation  
264 features and alteration characteristics are preserved in the cores, even in highly fractured and/or  
265 sheared intervals. The cores highlight a highly heterogeneous lateral and vertical distribution of  
266 ultramafic and mafic rocks that host a range of alteration styles and extent of deformation (Figs.  
267 2 and 3).

268

269 Of the core recovered from the six sites across the southern wall (from west to east: M0071,  
270 M0072, M0069, M0076, M0068, M0075; Figs. 1a and 2), serpentized harzburgite and dunite  
271 make up 44% of the core by length. Other major rock types include basaltic rocks and  
272 metadolerites (combined 24%) and schistose metasomatic rocks with varying proportions of talc,

273 amphibole and chlorite (11%). Minor lithologies include calcareous sedimentary units (8%), and  
274 gabbroic rocks (4%). In comparison, previous dredging and Alvin dive campaigns at the  
275 southern Atlantis Massif recovered a similar percentage of ultramafic rocks (45% of total  
276 samples collected), but a higher percentage of gabbroic rocks (24%), metasomatic rocks (22%)  
277 and sediments (15%), and less basaltic and doleritic rocks (5%) (Schroeder and John, 2004;  
278 Boschi et al., 2006a; Karson et al., 2006). The proportion of gabbro to peridotite was less than at  
279 IODP Site U1309, where 1408m of gabbroic rocks were recovered; however, the proportion of  
280 dolerite was comparable (Blackman et al., 2006; McCaig and Harris, 2012). A synthesis of the  
281 lithological contacts, mineralogies and off shore analyses of the key sites are given in  
282 Appendixes A through J.

283  
284 The ultramafic rocks are dominated by harzburgites punctuated by intervals of dunite and minor  
285 pyroxenite veins. Gabbroic rocks occur locally as zones of melt impregnation (tens of  
286 centimeters thick) and veins at Sites M0068, M0071, M0072 and M0076 (Fig. 2). The  
287 harzburgites and dunites exhibit protogranular textures and are extensively serpentinized.  
288 Intervals of weakly porphyroclastic serpentinized peridotites were rare and localized.  
289 Serpentinized dunites are found exclusively as discrete intervals alternating with harzburgite and  
290 likely represent relict mantle melt channels or domains of melt-rock interaction (Kelemen et al.,  
291 1992; Nicolas, 1986). Mantle melt-rock reaction textures including vermicular to subhedral  
292 spinels (e.g., Nicolas and Prinzhofer, 1983) and pyroxene veins were also observed. The  
293 distribution of gabbro rocks is highly heterogeneous downhole and there was an absence of  
294 continuous, coherent sections of gabbroic core. Rare magmatic fabrics characterized by diffuse  
295 but planar centimeter-scale banding/layering of igneous minerals in gabbroic rocks were

296 recovered in Hole M0068B. Dolerite intrusions, basaltic rocks and local domains of  
297 hyaloclastites represent the latest stage of magmatic activity. Metamorphosed dolerite intrusions  
298 ranging from a few cm to several meters in thickness were recovered at the central and eastern  
299 sites, and some dolerite intervals in Hole M0075B show chilled margins against fault rocks (see  
300 Fig. F5 in Früh-Green et al., 2017c). Dolerites and metadolerites as well as poorly vesicular  
301 aphanitic to microcrystalline basalts with glassy margins also occur as mm-dm sized components  
302 within the sedimentary breccias. The dolerites were variably altered, while basalts were often  
303 fresh, with no sign of metamorphism.

304  
305 All types of variably altered and deformed ultramafic and mafic rocks occur as clasts in  
306 sedimentary breccias overlying the basement sequences and as fault scarp deposits. The  
307 sedimentary cap rocks include basaltic breccias with foraminiferous carbonate sand and/or  
308 lithified foraminiferous carbonate matrix. Fresh and partially palagonitized glass in basaltic  
309 components and hyaloclastites were observed in some of the breccias and in some cores  
310 containing carbonate sediment.

311

### 312 *3.2.2 Serpentinization and metasomatism*

313 The IODP Expedition 357 cores reveal a high degree of alteration and intervals with variable  
314 metasomatic overprinting in the ultramafic rocks. Different types of alteration are distinguished  
315 depending on protolith: serpentinization, talc-amphibole-chlorite metasomatism and oxidation in  
316 the ultramafic rocks; and hydration, oxidation, and local Ca-metasomatism/chloritization along  
317 contacts between doleritic and gabbroic domains and serpentinites. The sequence of alteration



318 textures and the associated mineralogical assemblages vary between sites and downhole in some  
319 cases (Früh-Green et al., 2017c, d,e and f).

320

321 Serpentinization is common in the ultramafic rocks at all sites and occurs as pervasive alteration  
322 with extensive to complete replacement of the primary mineralogy, forming mesh textures after  
323 olivine, bastites (lizardite  $\pm$  chrysotile) after orthopyroxene, and different generations of  
324 serpentine veins (Fig. 4). A detailed study of the textures and mineralogies of the serpentinized  
325 serpentinites combined with *in situ* major and trace element analyses in primary phases and  
326 serpentine minerals is given in Rouméjon et al. (2018). These are used to make a model for the  
327 development of alteration heterogeneities at the Atlantis Massif and are summarized briefly here.  
328 Hydration of olivine led to a typical serpentine mesh texture, which is characterized by mesh  
329 cells, tens to hundreds of microns in size, delimited by microfractures that initially crosscut the  
330 olivine. Lizardite mesh rims form the outer part of cells, whereas the mesh cores are made up of  
331 poorly crystallized lizardite and/or chrysotile. Magnetite tends to crystallize in the mesh rims and  
332 concentrates along microfractures. Progressive fluid infiltration and serpentinization is evident  
333 by recrystallization of mesh textures to chrysotile-polygonal serpentine or antigorite, and by  
334 multiple sets of veins with variable infillings (Fig. 4; see also Rouméjon et al., 2018). The  
335 orthopyroxenes also show overprinting relationships with replacement by serpentine, talc,  
336 tremolite and/or chlorite.

337

338 Although the depth of penetration was limited, the abundance of gabbroic intrusions appears to  
339 increase from west to east and is associated with talc-amphibole-chlorite metasomatism and in  
340 some cases chlorite blackwall formation. Multiple generations of amphibole are observed in the

341 gabbroic domains, reflecting progressive alteration from amphibolite to greenschist-facies  
342 conditions during exhumation, as described in previous studies (Schroeder and John, 2004;  
343 Boschi et al., 2006a). Metasomatism is characterized by varying proportions of talc, chlorite and  
344 tremolitic amphibole and is a common feature at the central and eastern sites, evident as pale  
345 greenish-white domains or vein networks (Figs. 3b and d). Talc-metasomatism is rare at the  
346 western Site M0071 and is most prevalent in Hole M0072B near Lost City (Fig. 2). It develops  
347 both as pervasive, irregular patches in the serpentinites or as localized alteration associated with  
348 mafic intervals, enclosing serpentinitized harzburgite on centimeter to decimeter scales (Figs. 5  
349 and 6). The metasomatic domains are locally deformed and the talc-rich zones are commonly  
350 sheared, forming intervals of talc-amphibole-chlorite schists. Talc generally replaces mesh  
351 textures or forms in veins in the serpentinites, whereas tremolitic amphibole and chlorite  
352 assemblages are found in mafic domains and at contacts between serpentinite and gabbro or  
353 metagabbro, or in domains that have been infiltrated by mafic melts (Figs. 5 and 6). In some  
354 sections, amphibole and chlorite appear to have formed prior to talc. Relict olivine is also found  
355 in a number of cores in the central and eastern sites (Holes M0068, M0072, M0076) where talc-  
356 amphibole-chlorite metasomatism and/or chlorite-rich alteration is most prevalent.

357  
358 Metasomatism is particularly pronounced in Hole M0072B, where complex zoned intervals  
359 (approximately 5 cm thick) with mafic lenses adjacent to chlorite-rich blackwalls are repeatedly  
360 present over a few meters. Exceptional relationships between mafic intrusions (possibly doleritic  
361 or microgabbro), talc  $\pm$  amphibole  $\pm$  chlorite zones, and serpentinitized dunite and harzburgite are  
362 observed in Cores M0072B-6R1 (Fig. 5d) and M0072B-7R1 (Fig. 6). The mafic intrusions in  
363 these cores have pale brown to pinkish-brown central domains that are surrounded by external

364 dark green domains made up mostly of chlorite (chlorite blackwall), which in turn grade into  
365 talc-amphibole-rich domains at the contact to the serpentinites. The pinkish brown domains were  
366 originally described as rodingites (Früh-Green et al., 2017d), which have been found during  
367 previous sampling campaigns along the southern wall of the Atlantis Massif (Boschi et al.,  
368 2006a). However, subsequent analyses have yet to identify typical Ca-Al silicates, such as  
369 epidote (clinozoisite), diopside, prehnite, (hydro)garnet or vesuvianite, which are commonly  
370 found in rodingites in similar associations with serpentinites. Instead, preliminary X-ray  
371 diffraction (XRD), micro-Raman spectroscopy and microprobe analyses (unpublished data)  
372 indicate that these zones are indeed Ca-rich but are made up of chlorite and fine-grained  
373 aggregates of anorthite  $\pm$  tremolitic and/or pargasitic amphibole. The association of chlorite and  
374 anorthite in these domains could result from higher temperatures of alteration than are typically  
375 associated with rodingite ( $> \sim 350^\circ\text{C}$ ). Anorthite may also form from fluids with higher  $\text{CO}_2$   
376 concentrations (Rice, 1983).

377  
378 Although brucite occurs in the actively venting carbonate structures at Lost City (Kelley et al.,  
379 2001; Früh-Green et al., 2003; Ludwig et al., 2006) and is a common product of serpentinization  
380 reactions, it has not been found in previous studies of the basement rocks of the Atlantis Massif  
381 (e.g., Boschi et al., 2006a; 2008). In the IODP Expedition 357 cores, brucite could not be  
382 detected visually, microscopically or with XRD on bulk rock samples (Früh-Green et al.,  
383 2017c,d,e). In addition, a brucite signature is absent in micro-Raman spectra, which together  
384 with nearly stoichiometric serpentine compositions of the mesh texture serpentine minerals  
385 (Rouméjon et al., 2018; Rouméjon et al., this issue) strongly suggest that brucite is absent in the  
386 serpentinized peridotites that make up the southern wall of the Atlantis Massif. The absence (or

387 dissolution) of brucite and abundance of talc in the metasomatic assemblages may be a  
388 consequence of high Si activities in the fluids during progressive hydrothermal alteration along  
389 the detachment fault zone and/or high alteration temperatures (above 350°C) during denudation  
390 of the mantle.

391  
392 Finally, later-stage oxidation of the serpentized harzburgites and dunites is characterized by  
393 reddish to brown alteration, occurring as both pervasive and localized features, and is commonly  
394 associated with calcium carbonate veins (Fig. 3a). Overprinting relationships in the ultramafic  
395 rocks demonstrate an overall progression from local amphibole-chlorite alteration to  
396 serpentinization to talc ±amphibole ±chlorite metasomatism and later oxidation.

397  
398 Hydration of the dolerites and basalts manifests as pervasive background alteration with  
399 moderate to high intensity accompanied by alteration halos that flank veins. Secondary minerals  
400 vary depending on the temperature of alteration, with dolerites dominated by greenschist-facies  
401 minerals (chlorite, amphibole, and epidote), and basalts by low-temperature oxidation to iron  
402 oxyhydroxides and clays. Epidote occurs as a dominant vein mineral in metadolerites in Hole  
403 M0069A often with vein halos dominated by chlorite. Chilled margins in dolerite dikes that have  
404 intruded into talc-amphibole-chlorite schists are observed at the most eastern Site M0075.

405 Hydration of gabbros is generally associated with chlorite-amphibole assemblages.

406  
407 Hydrothermal veins are present in all rock types. Vein minerals include serpentine, talc, chlorite,  
408 amphibole, epidote, quartz, and calcium carbonate. The veins are often complex, with multiple  
409 infillings and internal textures, highlighting a protracted formation history. Crosscutting

410 relationships are also complex, with the same veins observed both crosscutting and being  
411 crosscut by a second vein type. The occurrence of calcium carbonate veins was surprisingly  
412 limited in the recovered cores. Carbonate veins are more prevalent in the sites around the Lost  
413 City hydrothermal field, where they occur mostly within entirely serpentinized dunites and  
414 harzburgites. At the western Site M0071, calcium carbonate veins in the serpentinites predate  
415 fractures that are infilled with foraminiferous carbonate sand (Fig 3a), suggesting open fractures  
416 at the top of the detachment fault zone, as described by Schroeder et al. (2002) based on *Alvin*  
417 dive samples.

418

### 419 *3.2.3 Structures and deformation history*

420 The drilled sites are located along a roughly spreading-parallel, 8.5 km transect (west–east) in  
421 various positions (trough or wall/flank) relative to individual corrugations of the detachment  
422 fault over the southern wall of Atlantis Massif (Fig. 1). Despite the fact that a number of the  
423 holes recovered rocks that are considered not to be *in situ*, generalizations can be made about the  
424 structural history recorded (Früh-Green et al., 2017c,d,e,f). As in IODP Hole U1309D at the  
425 central dome of the Atlantis Massif (Blackman et al., 2006), strongly deformed microstructures  
426 formed at high temperatures are rare in the IODP Expedition 357 cores. The majority of the  
427 recovered cores show amphibolite- to greenschist-facies, semibrittle and brittle deformation  
428 (Figs. 3 and 6), which contrasts with previous studies of samples recovered by submersible and  
429 by dredging that document higher temperature, high strain conditions in parts of the southern  
430 wall of the massif (Boschi et al., 2006a; Karson et al., 2006; Schroeder and John, 2004). Fault  
431 rocks in shear zones preserved in the cores are dominated by anastomosing intervals of variable  
432 intensity, with schistose amphibole  $\pm$  talc  $\pm$  chlorite zones up to tens of centimeters thick. The

433 schistose shear zones contain undeformed dolerite intrusions with preserved chilled margins;  
434 elsewhere, dolerite sheets record brittle and semibrittle deformation textures indicating repeated  
435 magmatism and faulting. Extensive intervals of flattened breccia are associated with dolerites but  
436 often contain clasts of fault rocks derived from other lithologies. Some breccia clasts show relicts  
437 of higher temperature amphibolite facies deformation, as do serpentinized intervals in the  
438 margins of talc-tremolite-chlorite schist zones. Intense cataclastic intervals and possible fault  
439 gouge occur within some breccias and also as thin intervals within the schistose shear zones.  
440 Discrete fault planes occur in most cores with a range of orientations, but lineations are generally  
441 shallow on both steep and shallow fault planes. An important observation is that the serpentinites  
442 are almost invariably statically altered, with no schistose serpentine developed and only  
443 occasional cataclastic seams. Strain within serpentinite intervals seems to be almost entirely  
444 localized within metasomatic talc-tremolite-chlorite horizons.

445

### 446 *3.3 Bulk rock geochemistry*

447 A wide range of major and trace element bulk rock compositions reflect the differences in rock  
448 type as well as the type and extent of alteration (Table 2, Figs. 7, 8 and 9). Independent of site  
449 location, the talc-amphibole-chlorite schists typically have high SiO<sub>2</sub> contents, ranging from 50-  
450 60 wt%, and low MgO/SiO<sub>2</sub> ratios (0.45 – 0.51) as well as lower loss on ignition (LOI: 4.3 – 5.3  
451 wt%) than the serpentinites (LOI: 11.95 – 13.8 wt%). The serpentinized ultramafic rocks have  
452 the highest MgO/SiO<sub>2</sub> ratios (0.96 – 1.19) and variable but high Cr (up to 29,698 ppm in Hole  
453 M0069) and Ni (up to 14,590 ppm in Hole M0071A) contents. Overall, the talc-amphibole-  
454 chlorite schists (and in some cases the impregnated/metasomatized ultramafic rocks) are richer in  
455 Al<sub>2</sub>O<sub>3</sub>, Na<sub>2</sub>O, CaO, TiO<sub>2</sub>, and depleted in Fe<sub>2</sub>O<sub>3</sub> (Fig. 7). The talc schists are also enriched in Cr

456 and Ni relative to the gabbroic rocks and dolerites but have lower concentrations than the  
457 ultramafic lithologies (Fig. 8). Samples from Hole M0068B exhibit the highest SiO<sub>2</sub>, CaO, and  
458 Na<sub>2</sub>O contents, but the lowest Al<sub>2</sub>O<sub>3</sub> and Fe<sub>2</sub>O<sub>3</sub> contents. The most altered dolerites and gabbros  
459 have characteristically low SiO<sub>2</sub> concentrations (26.2 – 31.6 wt%), high Fe<sub>2</sub>O<sub>3</sub> (18.8 – 32.1 wt%)  
460 and low Ni and Cr (Fig. 8), which reflects the high modal abundance of chlorite in these rocks  
461 and suggests Si mobility and loss during alteration (Fig. 9). The Mg and Ni concentrations of the  
462 IODP Expedition 357 serpentinites and impregnated serpentinites are higher than those  
463 recovered during IODP Expeditions 304-305 and likely reflects the more primitive nature of the  
464 mantle peridotites recovered along the southern wall. The gabbroic compositions are similar to  
465 the IODP Hole U1309D gabbros, but the dolerites and metadolerites have higher Ni  
466 concentrations and may be the result of a higher primary modal abundance of olivine (Fig. 9).

467  
468 The Rare Earth Element (REE) patterns group by lithology and show a weakly defined  
469 enrichment from west to east (Fig. 10) and some variations downhole. The serpentinitized  
470 ultramafic rocks have relatively flat to slightly light REE (LREE) depleted chondrite-normalized  
471 patterns (i.e., typically centered around 1 or below). The impregnated/metasomatized  
472 serpentinites from Hole M0072B exhibit values slightly higher than 1. Dolerites and gabbros  
473 exhibit moderate LREE depletions with values ranging between 1 and 10. Two of the talc-  
474 amphibole-chlorite schists have REE patterns resembling the impregnated/metasomatized  
475 samples. Positive and negative europium anomalies were observed but do not correlate with a  
476 particular lithology or site. Along with correlated Mg# and Ni abundances (Fig. 8), geochemical  
477 trends in the serpentinitized ultramafic rocks include a common uranium positive anomaly (the  
478 intensity of which decreases in impregnated / metasomatized samples) (Früh-Green et al.,

479 2017c,d,e) and enriched lithium, cerium, and strontium anomalies in the central sites (Table 2).  
480 Such anomalies are commonly related to alteration processes, either from hydrothermal  
481 alteration or from late interaction with seawater on the seafloor. Rouméjon et al. (2018)  
482 document regional trends in trace and REE element compositions in serpentine minerals  
483 compared to primary olivine and attribute the regional and downhole variations to mobilization  
484 of elements during the successive stages of exhumation as a result of early melt emplacement,  
485 serpentinization-related fluid-rock interaction, and later fluid-rock interaction. LREE  
486 enrichments due to the proximity with metagabbros or metadolerites are particularly observed in  
487 samples from Holes M0068B and M0072B (see also Boschi et al, 2006a) and contribute to the  
488 downhole variations.

489

#### 490 *3.4 Volatile concentrations*

491 Elevated bottom water gas concentrations recorded by the sensor package and water sampling  
492 confirmed that serpentinization is on-going at the Atlantis Massif (Figs. 11 and 12). Water  
493 samples before and after drilling indicated “hot spots” of dissolved hydrogen over Sites M0068,  
494 M0072, M0069, M0070 and M0071, with the highest concentrations of 323 nM measured in  
495 Hole M0072B. Elevated concentrations of methane were found over Sites M0072, M0070, and  
496 M0071 (Fig. 11, Table 1; see also Table T12 in Früh-Green et al., 2017c). A CTD cast directly  
497 over the Lost City hydrothermal vents (Site M0072) just south of the central drill sites had  
498 significantly elevated methane and hydrogen (35–48 nM and 196–267 nM, respectively). On a  
499 regional scale, hydrogen concentrations tended to be highest in the central sites and at the eastern  
500 Site M0068, which may reflect active serpentinization in the vicinity of the Lost City  
501 hydrothermal field (Fig. 11; Table 1). However, the interpretation of the regional-scale influence



502 on methane and hydrogen fluxes out of the basement is ambiguous since the depth of penetration  
503 into the basement was limited to <20 mbsf.

504

505 In addition to elevated dissolved gas concentrations measured in the fluids, gas bubbles were  
506 observed issuing from the hole and around the drill base during operations at Site M0070, even  
507 when coring had stopped (Fig. 13). The bubbles could not be sampled directly with the seabed  
508 drills and thus their composition remains unknown. Bathymetry indicates that Site M0070 lies  
509 west of the western limit of the preserved striated detachment surface of Atlantis Massif (Fig. 1)  
510 at the foot of a ~30 m high irregular mound (Figure F2A in Früh-Green et al., 2017f). The three  
511 holes penetrated the same structural unit composed of either loose or cemented basalt clasts with  
512 vesicles and glass within a carbonate matrix. The mound is likely a volcanic cone that has  
513 undergone faulting and/or mass wasting and, thus, we cannot exclude volcanic gases as a source  
514 of the bubbles observed at this site.

515

516 In addition to the water sampling observations, the drill-mounted sensors recorded peaks in  
517 methane and pH that correlated with sharp decreases in oxidation-reduction potential (ORP) at  
518 many sites (Figure 12, Früh-Green et al., 2017c,d,e,f). Low ORP (or Eh) reflects reducing  
519 conditions and can be interpreted as elevated hydrogen concentrations and/or other reduced  
520 components (such as reduced iron and hydrogen sulphide) in the fluid. The ORP sensor does not  
521 respond to methane. In some cases, excursions in the sensor signals were observed while  
522 drilling, which suggests that horizons that were penetrated released reduced basement fluids and  
523 volatiles into the drilling fluid. In other cases, we observed variations in the methane, pH and  
524 ORP signals even when no drilling operations were underway or when the drills touched down

525 on the seabed, suggesting that diffuse reduced fluids may be present at the top of the massif. In  
526 many cases we observed strong negative spikes in the ORP signals without a corresponding  
527 methane signal, which points to hydrogen and/ or other reduced phases being released into the  
528 drilling fluids. Due to limited core recovery, we were not able to clearly correlate the excursions  
529 in sensor data with specific horizons or rock types. On a regional scale, negative spikes in ORP  
530 were observed in most of the holes in the central sites, which is consistent with the higher  
531 dissolved H<sub>2</sub> and CH<sub>4</sub> concentrations at these sites and may reflect hydrothermal circulation  
532 related to the Lost City hydrothermal field.

533  
534 It is worth noting that the dissolved methane concentrations were monitored with a Franatech  
535 METS sensor. Post-cruise evaluation of this sensor revealed that it responds to both CH<sub>4</sub> and H<sub>2</sub>  
536 with a response factor of 1 to 0.02, respectively. This complicates interpretations of the output of  
537 this sensor because H<sub>2</sub> concentrations typically exceed those of CH<sub>4</sub> in this environment. For  
538 example, in Lost City hydrothermal fluids, the H<sub>2</sub>/CH<sub>4</sub> ratio varies from 0.5 to 9.2 (Proskurowski  
539 et al, 2008). Where we measured bottom water concentrations from CTD casts, CH<sub>4</sub> was often  
540 below our detection limit (0.7 nM); however, at some sites both H<sub>2</sub> and CH<sub>4</sub> were present and the  
541 H<sub>2</sub>/CH<sub>4</sub> ratio ranged from 5.5 to 20.9. In samples taken in the Lost City plume, the average ratio  
542 was 5.3. Samples from the drill-mounted Niskin bottles yielded H<sub>2</sub>/CH<sub>4</sub> ratios ranging from 1.2  
543 at Site M0070A to 167 at Site M0068B (see Table T12 in Früh-Green et al., 2017c). Although  
544 we were unable to make quantitative estimates of volatile concentrations from the sensor data,  
545 the METS sensor likely recorded both H<sub>2</sub> and CH<sub>4</sub>, and it is possible that the output values we  
546 observe represent H<sub>2</sub> concentrations that are a factor of 50 times higher than the actual recorded

547 values given as CH<sub>4</sub> concentrations. Horizons with high H<sub>2</sub> concentrations are also indicated by  
548 the fact that elevated CH<sub>4</sub> signals often correlated with strong decreases in ORP.

549

### 550 *3.5 Microbiology sampling*

551 To accomplish the microbiology-related objectives of the expedition, an extensive program was  
552 carried out on board the ship to collect whole-round core samples immediately after core  
553 retrieval, curation, and scanning with the multisensor core logger to enable preservation of  
554 ephemeral microbiological properties. This program included (1) frozen preservation of core  
555 material for DNA- and lipid-based analyses in shore-based laboratories, (2) establishment of  
556 enrichment incubations on the ship (at ambient or *in situ* pressure) to assess the potential for  
557 various microbial metabolisms, (3) collection of samples to evaluate the performance of the  
558 contaminant tracer delivery, (4) preservation of samples for biomass determination via cell  
559 counting, and (5) collection of parallel samples for spatial and isotopic geochemical  
560 determination, particularly focused on carbon and minerals.

561

562 A major technical development for this expedition to enable microbiological analysis was  
563 establishing the delivery system for adding a synthetic tracer (PFC) into the drilling fluids to  
564 monitor the possibility of drilling-induced contamination (Orcutt et al., 2017). Samples of core  
565 barrel liner fluids, sensor package Niskin bottles, and exterior and interior pieces of whole-round  
566 core were collected to quantify the concentration of PFC tracer added during drilling operations  
567 and track its potential distribution into samples. After overcoming some technical difficulties  
568 with the metering pump in the delivery system, we established that PFC was delivered at  
569 saturating (>1 mg/L) concentrations into the drilling fluids (Orcutt et al., 2017). Moreover,

570 appropriate handling conditions combined with coherent core samples resulted in the absence of  
571 tracer from the interior of core samples (whereas less coherent materials suffered potential  
572 contamination from intrusion of tracer). Overall, implementation of the tracer injection system  
573 for seabed drill systems proved to work, and PFC concentrations on the exterior and interior of  
574 core samples could be used as a measure to assess the quality of the sample material for detailed  
575 microbiological and geochemical analyses (Orcutt et al., 2017).

576  
577 To obtain an initial assessment of microbial biomass in the core samples, cell abundance was  
578 determined on the ship and onshore at the Kochi Core Center (Japan) in an ultraclean laboratory.  
579 Direct counting was made with an epifluorescence microscope following cell separation from  
580 flame sterilized interior portions of subsamples. To enable low levels of cell detection, great care  
581 was taken onshore and offshore to minimize contamination of samples (Früh-Green et al., 2017b;  
582 Morono et al., 2017), resulting in a limit of detection of 9.8 cells cm<sup>-3</sup>. Cell abundance in the  
583 core samples was variable and relatively low, ranging from tens to thousands of cells/cm<sup>3</sup>, with  
584 many of the basement samples often below the minimum quantification limit of 9.8 cells cm<sup>-3</sup>  
585 (Fig. 14). Cell counts in the interior portions of the basement rocks ranged from <10 to 6.5 x 10<sup>2</sup>  
586 cells cm<sup>-3</sup>, with one sample from Hole M0071A yielding 4.1 x 10<sup>3</sup> cells cm<sup>-3</sup>. Excluding the  
587 short core obtained at Site M0074 (because of contamination issues with core handling), the  
588 highest cell counts were found in the sediments in Hole M0069A near the contact to the  
589 basement, reaching up to 1.6 x 10<sup>4</sup> cells cm<sup>-3</sup> at 5.46 mbsf, and decreased rapidly to <10<sup>2</sup> cells  
590 cm<sup>-3</sup> in the underlying basement rocks. The deepest samples were from this hole (at 14.6 mbsf),  
591 where 10-24 cells cm<sup>-3</sup> were measured in the serpentinites. A similar trend was observed at Hole

592 M0072B, with up to  $5 \times 10^2$  cells  $\text{cm}^{-3}$  within the top meter of the hole and decreasing to  $<20$   
593 cells  $\text{cm}^{-3}$  below 6.5 mbsf (Fig. 14).

594

595 The cell densities in the IODP Expedition 357 drill cores are distinctly lower than in the actively  
596 venting Lost City carbonate towers ( $10^7$  to  $10^8$  per gram of wet weight; Kelley et al., 2005). They  
597 are also low in comparison to cell densities in fluids sampled in actively serpentinizing  
598 environments on land, which are typically less than  $10^5$  cells  $\text{ml}^{-1}$ , and as low as  $10^2$  cells  $\text{mL}^{-1}$ ,  
599 although continental sites of serpentinization represent different niches within the subsurface  
600 ecosystem (e.g., Schrenk et al., 2013; Brazelton et al., 2017). These cell densities are also lower  
601 than in mafic seafloor cores, which have been estimated at  $\sim 10^4$  cells per gram of rock  
602 (Jørgensen and Zhao, 2016). Overall, the strict sampling handling protocols allowed for very  
603 low limits of microbial cell detection, and our results show that the Atlantis Massif subsurface  
604 contains a relatively low density of microbial life compared to other seafloor crustal and  
605 serpentinizing systems. This low density suggests that something may be limiting life in this  
606 subsurface habitat compared to the other habitats, such as energy availability, high pH, or low  
607 carbon dioxide availability, but further analyses are required to determine this.

608

#### 609 **4. Implications for understanding oceanic core complex processes**

610 Expedition 357 was the first IODP expedition to successfully use seabed drills to acquire intact  
611 shallow mantle sequences at the top of the footwall of an oceanic detachment fault zone and to  
612 monitor borehole fluids while drilling. This expedition provides insights into magmatic, tectonic  
613 and alteration processes of an oceanic core complex that is actively undergoing serpentinization  
614 and has the potential to sustain a unique subsurface biosphere. The cores have exceptionally

615 well-preserved contacts and show strong lateral and vertical variations (from cm to m scale) in  
616 rock type and alteration assemblages that are a consequence of multiple phases of magmatism,  
617 fluid-rock interaction and mass transfer along the detachment fault zone. The results of this  
618 expedition are expected to address fundamental questions that were part of the motivation for the  
619 expedition (Früh-Green et al., 2015), such as: How are seafloor spreading and mantle melting  
620 linked to ocean crustal architecture? How do oceanic detachment faults develop and facilitate  
621 hydrothermal circulation? How do they affect the development of alteration patterns and the  
622 evolution of the deep biosphere in these environments?  
623  
624 IODP Expedition 357 sampled only the very shallowest level of the detachment fault zone and  
625 overlying talus blocks at the top of the massif. However, this is the first time that clear  
626 relationships of gabbro and dolerite hosted by mantle peridotite along the southern wall of  
627 Atlantis Massif have been documented. These relationships imply that melts are generated  
628 beneath volcanic-poor ridge segments at ridge-transform intersections, but much of the melt may  
629 be trapped in the mantle as it turns into lithosphere beneath the ridge axis, rather than migrating  
630 upward to form a continuous magmatic crust. Based on high-resolution ion microprobe (*i.e.*,  
631 SHRIMP) U-Pb zircon ages from IODP Hole 1309D and broadly spaced samples collected along  
632 the southern ridge of Atlantis Massif, Grimes et al. (2008) document a protracted history of  
633 accretion in the footwall. They calculate a detachment fault slip rate of  $28.7 \pm 6.7$  mm/a, which  
634 implies significant asymmetric plate spreading (up to 100% on the North American plate) for at  
635 least 200 ka during core complex formation. Our results are consistent with previous studies that  
636 indicate that ongoing magmatic activity associated with asymmetric plate spreading results in a  
637 heterogeneous mafic and ultramafic lithosphere with late dolerite intrusions exposed in the

638 denuded footwall, whereas accretion of volcanic seafloor persists in the hanging wall (Cannat et  
639 al., 2006; Grimes et al., 2008; Ildefonse et al., 2007; John and Cheadle, 2010; Karson et al.,  
640 2006; McCaig and Harris, 2012; Smith et al., 2006).

641  
642 The volume of gabbros in the southern wall of the Atlantis Massif and their mode of intrusion as  
643 thin lenses are distinct from the thick gabbroic sequence recovered at IODP Site U1309 (IODP  
644 Expeditions 304 and 305) at the central dome (Blackman et al., 2006; Ildefonse et al., 2007;  
645 McCaig et al., 2010; McCaig and Harris, 2012). Although a direct comparison of the two drilling  
646 campaigns is difficult to make because of depth of penetration, and the possible tectonic control  
647 on emplacement of rock sections, both campaigns yield important information about accretion  
648 and alteration processes as well as regional heterogeneities associated with the architecture and  
649 evolution of OCCs. The surface of the central dome was cored at IODP Hole U1309B, where  
650 dike rocks and basalts were recovered, and a few pebbles of talc schist together with highly  
651 altered basalt and dolerite were recovered in IODP Hole U1309H (Blackman et al., 2006; John et  
652 al 2009). In addition, Alvin sampling during cruise AT3-60 in 2000 (MARVEL expedition;  
653 Blackman et al., 2002) recovered one talc schist sample (sample 3642-1309; see Boschi et al.,  
654 2008) along dive tracks in the vicinity of IODP Site U1309. Metasomatic talc-amphibole-chlorite  
655 rocks are considered key components of detachment fault zones (e.g., Escartin et al., 2003;  
656 Boschi et al., 2006a,b; McCaig et al., 2010) and pre-date dolerite diking events and basaltic  
657 eruptions (Karson et al. 2006; McCaig and Harris, 2012). Although not abundant, the occurrence  
658 of talc schists in the central dome of the Atlantis Massif hints at the presence of a thin  
659 detachment fault zone in this area. However, on a regional scale, the newly acquired multibeam

660 data (Fig. 1) clearly allow the corrugated surface related to the detachment fault zone to be  
661 distinguished.

662

663 The mineralogical assemblages, alteration textures, and bulk rock chemistries recorded in the  
664 IODP Expedition 357 drill cores indicate progressive seawater infiltration along the detachment  
665 fault and into the footwall, pointing to an important role of the mafic intrusions in controlling  
666 fluid chemistry and metasomatism. Early high temperature, amphibolite-facies alteration and  
667 ductile deformation features have been reported from studies of dredged and submersible  
668 sampling of the southern wall (Boschi et al., 2006a; Karson et al., 2006; Schroeder and John,  
669 2004), but such features are less common in the IODP Expedition 357 drill cores. In contrast,  
670 alteration in the shallow IODP Expedition drill cores is dominated by serpentinization processes,  
671 brittle deformation and mass transfer between mafic and ultramafic lithologies under  
672 greenschist-facies conditions.

673

674 The occurrence of gabbroic intrusions is associated with talc-amphibole-chlorite metasomatism  
675 and local blackwall formation and appears to increase from west to east. Metasomatism and talc  
676 precipitation are most prevalent at contacts between mafic and ultramafic domains (Figs. 5 and  
677 6.). A systematic overprinting of serpentinite by talc- and chlorite-rich assemblages is associated  
678 with the occurrence of variably thick (micro)gabbroic lenses and points to silica mobility and  
679 channelled fluid flow at varying depths within the detachment fault zone (see also Boschi et al.,  
680 2006, 2008). The geochemical influence of the gabbroic intrusions and progressive fluid-rock  
681 interaction is also evident from REE enrichments measured in serpentine minerals and tends to  
682 increase from west to east (Rouméjon et al., 2018). The general trend to slightly larger volumes



683 of gabbroic intrusions from west to east (assuming the position of the drill holes roughly reflect  
684 differing original depths in the lithosphere) suggests that magmatic activity may have been  
685 greater at depth within the detachment fault zone before emplacement to their current locations.

686

687 The textural sequences and mineralogical assemblages in the ultramafic rocks reveal a transition  
688 between an initial pervasive phase of hydration along grain boundaries to produce mesh-textures  
689 in the serpentinites, with subsequent serpentinization and metasomatism focused along localized  
690 fluid pathways (Rouméjon et al., 2018). Alteration commences as the peridotites and gabbros are  
691 subjected to active hydrothermal circulation, but alteration of the dominant phase, olivine, to  
692 produce serpentine minerals will be limited to temperatures below approximately 500°C  
693 (Chernosky, 1973). Serpentinization of olivine becomes more effective below 350-400°C  
694 (Evans, 2004) and reaches maximum rates between 250°-300°C (Andreani et al., 2007; Martin  
695 and Fyfe, 1970; Malvoisin et al., 2012; McCollom 2016). Hydration is intense directly along the  
696 detachment fault zone, where permeability is expected to be highest (McCaig et al., 2007;  
697 McCaig et al., 2010), and progresses inside the footwall. When the fluids reach temperatures  
698 below ~350°C, efficient serpentinization commences and is recorded by the development of  
699 mesh texture at all sites. Based on zircon analyses and multicomponent magnetic remanence data  
700 in the central dome, Schoolmeesters et al. (2012) proposed a model for the thermal structure of  
701 the Atlantis Massif in which the 350°C isotherm corresponds to a depth of approximately 5 km  
702 below the surface. Thus, initiation of serpentinization would have occurred at significant depths  
703 and early in the exhumation history of the massif. The infiltration of seawater-derived  
704 hydrothermal fluids is facilitated by the closely-spaced microfracture networks that crosscut the  
705 olivine and result from combined thermal and tectonic stresses, enhanced by reaction-induced

706 permeability at the onset of serpentinization (Rouméjon and Cannat, 2014; Rouméjon et al.,  
707 2018). As the footwall reaches shallower crustal levels, fluid flow will likely be dominated by  
708 more continuous fracture planes that can channel hydrothermal fluids through the peridotite and  
709 form veins (Andreani et al., 2007; Rouméjon et al., 2018). The transition from more pervasive  
710 grain-boundary flow to localized or channeled flow is indicated by recrystallization of the mesh  
711 texture to chrysotile-dominated serpentine and by banded veins (Rouméjon et al., 2018;  
712 Rouméjon et al., this issue).

713

714 Talc formation postdates an early phase of serpentinization, and in some cases amphibole  
715 formation (see also Boschi et al., 2006a), but predates late-stage intrusions and alteration of some  
716 dolerite dikes and the extrusion of basalt, indicating that basaltic magmatism continued as the  
717 variably altered basement sequences were emplaced on the seafloor. Alternating metasomatic  
718 and serpentinized domains as well as irregular cross-cutting vein relationships in the IODP  
719 Expedition 357 cores from the central (M0072 and M0076) and eastern sites (M0068) emphasize  
720 the dynamic nature of the system with similar composition of veins forming at multiple times.

721 Textural relationships and the lateral and vertical distribution of metasomatic assemblages  
722 indicate that Si ± Ca ± Al mass transfer occurred locally at peridotite/gabbro or  
723 peridotite/dolerite contacts as well as through infiltration and interaction with Si-rich fluids along  
724 fractures to form talc-rich assemblages (see also Boschi et al., 2006a; McCaig et al., 2010;  
725 Rouméjon et al., 2018). In addition, the volume of carbonate veins was surprisingly low in the  
726 recovered cores, even in the sites directly above the Lost City hydrothermal field. This suggests  
727 that present-day fluid flow and hydrothermal activity at Lost City is localized by late normal  
728 faults that cut the southern wall (Denny et al., 2015).

729

730 The presence of the mafic lenses within the serpentinites – and their alteration products to  
731 mechanically weak minerals, such as talc, serpentine and chlorite – may also be critical to the  
732 development of the detachment fault zone and may enhance unroofing of upper mantle  
733 peridotites and lower crustal gabbroic rocks during seafloor spreading (Escartin et al., 2003;  
734 Schroeder and John, 2004; Boschi et al., 2006b). Talc in particular may be influential in  
735 lubricating and softening mylonitic shear zones and can lead to strain localization and focused  
736 hydrothermal circulation along such faults (see also McCaig et al, 2010). In fact, low-T  
737 detachment strain ( $< \sim 300^{\circ}\text{C}$ ) may actually be concentrated with time in the weak, talc-  
738 serpentine-rich rocks, creating a runaway system and allowing movement on the detachment  
739 fault zone to remain active while leaving a large portion of the exposed lithosphere undeformed.  
740 In addition, based on detailed studies of greenschist- to amphibolite-facies assemblages in  
741 metadolerites in the upper 130m of the IODP Site U1309D drill cores, McCaig and Harris (2012)  
742 argue that the detachment fault zone itself acts as a conductive boundary layer between gabbroic  
743 intrusions in the footwall and active hydrothermal circulation within the fault zone. They  
744 conclude that widespread occurrences of gabbro at high levels in the crust below detachment  
745 faults may be an expression of the same fundamental balance between magmatism and  
746 hydrothermal circulation that produces a layered structure at fast-spreading ridges.

747

748 Although alteration in the IODP drill cores is dominated by earlier phases of serpentinization and  
749 metasomatism associated with detachment faulting and denudation of mantle peridotites, wide-  
750 scale, active serpentinization at Atlantis Massif is indicated by elevated concentrations of  $\text{H}_2$  and  
751  $\text{CH}_4$  in bottom water sampled before and after drilling. Even at the transform fault,  $\text{H}_2$

752 concentrations in CTD casts were elevated (6.2 nM) relative to background seawater (<0.3 nM).  
753 Monitoring of the borehole fluids during drilling operations recorded numerous excursions in  
754 methane, temperature and ORP that often correlated with each other. The fact that the excursions  
755 occurred both while drilling as well as when no coring operations were taking place implies that  
756 horizons of reduced, and likely hydrogen-rich, fluids must exist in the basement rocks and that  
757 volatiles are being continuously expelled during active serpentinization at the Atlantis Massif.  
758 Active volatile expulsion was also indicated as bubbles emitting from Site M0070. The diffuse  
759 fluid flow indicated by the sensor package data and water sampling during IODP Expedition 357  
760 contrasts strongly with the focused flow associated with the actively venting Lost City  
761 hydrothermal field. The detachment fault zone seems to play a passive role in channelling the  
762 basement fluids. Instead, present-day hydrothermal fluid flow is likely controlled by late-stage  
763 normal faults cutting the southern wall (Fig. 1; see also Denny et al., 2015). In addition, the  
764 present-day hydrothermal fluids, characterized by high pH, low Si, and low metal concentrations  
765 are controlled by serpentinization reactions and are chemically distinct from the higher  
766 temperature fluids that were involved with mass transfer and metasomatism at deeper levels of  
767 the detachment fault zone and at earlier stages in the evolution of the Atlantis Massif.  
768  
769 A major achievement of IODP Expedition 357 was to obtain microbiological samples along the  
770 west-east lithospheric age profile, which will provide a better understanding of how microbial  
771 communities evolve as ultramafic rocks are emplaced on the seafloor. Our results indicate that  
772 the subsurface of the serpentinite basement of Atlantis Massif has relatively low biomass. We  
773 anticipate that on-going post-cruise microbiological studies will provide important constraints to  
774 address basic questions, such as what is the nature of microbial communities hosted by

775 serpentinizing rocks, and to what depth is microbial activity sustained? How do these vary with  
776 aging of the lithosphere? How do they differ from or interact with communities in sediments and  
777 mafic substrates in the same age crust? Because of the significant difference in volatile  
778 compositions and limited CO<sub>2</sub> stability at high pH, one can expect that biotopes hosted in  
779 serpentinizing environments will differ significantly from axial, basaltic-hosted vent systems in  
780 which CO<sub>2</sub> is a dominant volatile species. In addition, the mixing of oxidized seawater with  
781 highly reduced fluids leads to complex gradients in fluid chemistry and possibly temperature that  
782 may influence microbial distribution and activity. Substantially different habitats harboring  
783 various types of aerobic and anaerobic metabolisms may thus occur over a narrow spatial scale  
784 in these types of environments.

785

#### 786 **Acknowledgements**

787

788 We thank the captain and crew aboard the RRS *James Cook* and the ESO staff for their efforts  
789 and support during all phases of IODP Expedition 357. Funding by ECORD is gratefully  
790 acknowledged and each of the IODP Exp. 357 participants thanks their representative national  
791 funding agencies for IODP support to participate in the expedition and conduct post-cruise  
792 studies. This contribution was greatly improved by the thoughtful and thorough reviews from an  
793 anonymous reviewer and Nicholas Haymon.

794

#### 795 **Supplementary Material**

796 Appendix A. Synthesis of the lithological contacts, mineralogies and off shore analyses of the  
797 western Hole M0071A (IODP Expedition 357).

798

799 Appendix B. Synthesis of the lithological contacts, mineralogies and off shore analyses of the  
800 western Hole M0071B (IODP Expedition 357).

801

802 Appendix C. Synthesis of the lithological contacts, mineralogies and off shore analyses of the  
803 western Hole M0071C (IODP Expedition 357).

804

805 Appendix D. Synthesis of the lithological contacts, mineralogies and off shore analyses of the  
806 central Hole M0069A (IODP Expedition 357).

807

808 Appendix E. Synthesis of the lithological contacts, mineralogies and off shore analyses of the  
809 central Hole M0072B, IODP Expedition 357 (Part 1).

810

811 Appendix F. Synthesis of the lithological contacts, mineralogies and off shore analyses of the  
812 central Hole M0072B, IODP Expedition 357 (Part 2).

813

814 Appendix G. Synthesis of the lithological contacts, mineralogies and off shore analyses of the  
815 central Hole M0076B, IODP Expedition 357 (Part 1).

816

817 Appendix H. Synthesis of the lithological contacts, mineralogies and off shore analyses of the  
818 central Hole M0076B, IODP Expedition 357 (Part 2).

819

820 Appendix I. Synthesis of the lithological contacts, mineralogies and off shore analyses of eastern  
821 Hole M0068B (IODP Expedition 357).

822

823 Appendix J. Synthesis of the lithological contacts, mineralogies and off shore analyses of eastern  
824 Hole M0075B (IODP Expedition 357).

825

826

## 827 **References**

828 Alt, J.C., Shanks, W.C., III, 2003. Serpentinization of abyssal peridotites from the MARK area,  
829 Mid-Atlantic Ridge: sulfur geochemistry and reaction modeling. *Geochimica et Cosmochimica*  
830 *Acta* 67(4), 641–653.

831 Andreani, M., Mével, C., Boullier, A.-M., Escartin, J., 2007. Dynamic control on serpentine  
832 crystallization in veins: constraints on hydration processes in oceanic peridotites. *Geochemistry,*  
833 *Geophysics, Geosystems* 8(2), Q02012.

834 Blackman, D.K., Karson, J.A., Kelley, D.S., Cann, J.R., Früh-Green, G.L., Gee, J.S., Hurst, S.D.,  
835 John, B.E. Morgan, J., Nooner, S.L., Ross, D.K., Schroeder, T.J., Williams, E.A., 2002.  
836 *Geology of the Atlantis Massif (Mid-Atlantic Ridge, 30°N): implications for the evolution of an*  
837 *ultramafic oceanic core complex. Marine Geophysical Research* 23(5–6), 443–469.

838 Blackman, D.K., Ildefonse, B., John, B.E., Ohara, Y., Miller, D.J., MacLeod, C.J., the Expedition  
839 304/305 Scientists, 2016. *Proceedings of the Integrated Ocean Drilling Program, Volume*  
840 *304/305: College Station, TX, Integrated Ocean Drilling Program Management International,*  
841 *Inc., doi: 10.2204/iodp. proc.304305.2006.*

842 Boschi, C., Früh-Green, G.L., Delacour, A., Karson, J.A., Kelley, D.S., 2006a. Mass transfer and  
843 fluid flow during detachment faulting and development of an oceanic core complex, Atlantis  
844 Massif (MAR 30°N). *Geochemistry, Geophysics, Geosystems* 7(1), Q01004.

845 Boschi, C., Früh-Green, G.L., Escartin, J., 2006b. Occurrence and significance of serpentinite-  
846 hosted, talc-rich fault rocks in modern oceanic settings and ophiolite complexes. *Ofioliti* 31(2),  
847 123-134.

848 Boschi, C., Dini, A., Früh-Green, G.L., Kelley, D.S., 2008. Isotopic and element exchange during  
849 serpentinization and metasomatism at the Atlantis Massif (MAR 30°N): insights from B and Sr  
850 isotopes. *Geochimica et Cosmochimica Acta* 72(7), 1801–1823.

851 Brazelton, W.J., Baross, J.A., 2009. Abundant transposases encoded by the metagenome of a  
852 hydrothermal chimney biofilm. *ISME Journal* 3(12), 1420–1424.

853 Brazelton, W.J., Schrenk, M.O., Kelley, D.S., Baross, J.A., 2006. Methane- and sulfur-  
854 metabolizing microbial communities dominate the Lost City hydrothermal field ecosystem.  
855 *Applied and Environmental Microbiology* 72(9), 6257–6270.

856 Brazelton, W.J., Thornton, C.N., Hyer, A., Twing, K.I., Longino, A.A., Lang, S.Q., Lilley, M.D.,  
857 Früh-Green, G.L., Schrenk, M.O., 2017. Metagenomic identification of active methanogens and  
858 methanotrophs in serpentinite springs of the Voltri Massif, Italy. *PeerJ* 5:e2945  
859 <https://doi.org/10.7717/peerj.2945>.

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

863 Cannat, M., 1993. Emplacement of mantle rocks in the seafloor at mid-ocean ridges. *Journal of*  
864 *Geophysical Research: Solid Earth* 98(B3), 4163–4172.



865 Cannat, M., Sauter, D., Mendel, V., Ruellan, E., Okino, K., Escartin, J., Combier, V., and Baala,  
866 M., 2006. Modes of seafloor generation at a melt-poor ultraslow-spreading ridge. *Geology*  
867 34(7), 605–608.

868 Chernosky, J. V. J., 1973. An experimental investigation of the serpentine and chlorite group  
869 minerals in the system MgO-Al<sub>2</sub>O<sub>3</sub> – SiO<sub>2</sub> – H<sub>2</sub>O, Ph.D. thesis, Mass. Inst. of Tech- nol.,  
870 Cambridge.

871 Delacour, A., Früh-Green, G.L., Bernasconi, S.M., Schaeffer, P., Kelley, D.S., 2008. Carbon  
872 geochemistry of serpentinites in the Lost City hydrothermal system (30°N, MAR). *Geochimica*  
873 *et Cosmochimica Acta* 72(15), 3681–3702.

874 Denny, A.R., Kelley, D.S., and Früh-Green, G.L., 2015. Geologic Evolution of the Lost City  
875 Hydrothermal Field: *Geochemistry, Geophysics, Geosystems* 17, 375–394, doi:10.1002/  
876 2015GC005869.

877 Dick, H.J.B., Tivey, M.A., Tucholke, B.E., 2008. Plutonic foundation of a slow-spreading ridge  
878 segment: oceanic core complex at Kane Megamullion, 23°30'N, 45°20'W. *Geochemistry,*  
879 *Geophysics, Geosystems* 9(5), Q05014.

880 Escartín, J., Canales, J. P., 2011. Detachments in oceanic lithosphere: Deformation, magmatism,  
881 fluid flow, and ecosystems. *Eos, Transactions American Geophysical Union* 92(4), 31-31.

882 Escartín, J., Mével, C., MacLeod, C.J., and McCaig, A.M., 2003. Constraints on deformation  
883 conditions and the origin of oceanic detachments: the Mid- Atlantic Ridge core complex at 15  
884 °45' N. *Geochemistry, Geophysics, Geo- systems*, 4(8):1067.  
885 <http://dx.doi.org/10.1029/2002GC000472>.

886 Escartín, J., Andreani, M., Hirth, G., Evans, B., 2008. Relationships between the microstructural  
887 evolution and the rheology of talc at elevated pressures and temperatures. *Earth and Planetary*  
888 *Science Letters* 268(3–4), 463–475.

889 Evans, B. W., 2004. The Serpentinite Multisystem Revisited: Chrysotile Is Metastable.  
890 *International Geology Review*, 46(6), 479–506. <http://doi.org/10.2747/0020-6814.46.6.479>

891 Früh-Green, G.L., Kelley, D.S., Bernasconi, S.M., Karson, J.A., Ludwig, K.A., Butterfield, D.A.,  
892 Boschi, C., Proskurowski, G., 2003. 30,000 years of hydrothermal activity at the Lost City vent  
893 field. *Science* 301(5632), 495–498.

894 Früh-Green, G.L., Connolly, J.A.D., Plas, A., Kelley, D.S., Grobéty, B., 2004. Serpentinization of  
895 oceanic peridotites: implications for geochemical cycles and biological activity. In Wilcock,  
896 W.S.D., DeLong, E.F., Kelley, D.S., Baross, J.A., Cary, C., *The Seafloor Biosphere at Mid-*  
897 *Ocean Ridges*. *Geophysical Monograph* 144, 119–136.

898 Früh-Green, G.L., Orcutt, B.N., and Green, S., 2015. *Expedition 357 Scientific Prospectus: Atlantis*  
899 *Massif Serpentinization and Life*. International Ocean Discovery Program.  
900 <http://dx.doi.org/10.14379/iodp.sp.357.2015>.

901 Früh-Green, G.L., Orcutt, B.N., Green, S., Cotterill, C., and the Expedition 357 Scientists,  
902 2016. Expedition 357 Preliminary Report: Atlantis Massif Serpentinization and  
903 Life. International Ocean Discovery Program. <http://dx.doi.org/10.14379/iodp.pr.357.2016>

904 Früh-Green, G.L., Orcutt, B.N., Green, S.L., Cotterill, C., Morgan, S., Akizawa, N., Bayrakci,  
905 G., Behrmann, J.-H., Boschi, C., Brazelton, W.J., Cannat, M., Dunkel, K.G., Escartin, J.,  
906 Harris, M., Herrero-Bervera, E., Hesse, K., John, B.E., Lang, S.Q., Lilley, M.D., Liu, H.-Q.,  
907 Mayhew, L.E., McCaig, A.M., Menez, B., Morono, Y., Quéméneur, M., Rouméjon, S.,  
908 Sandaruwan Ratnayake, A., Schrenk, M.O., Schwarzenbach, E.M., Twing, K.I., Weis, D.,

909 Whattam, S.A., Williams, M., Zhao, R., 2017a. Expedition 357 summary, in Früh-Green,  
910 G.L., Orcutt, B.N., Green, S.L., Cotterill, C., and the Expedition 357 Scientists, Atlantis  
911 Massif Serpentinization and Life. Proceedings of the International Ocean Discovery Program,  
912 357: College Station, TX. <http://dx.doi.org/10.14379/iodp.proc.357.101.2017>.

913 Früh-Green, G.L., Orcutt, B.N., Green, S.L., Cotterill, C., Morgan, S., Akizawa, N., Bayrakci,  
914 G., Behrmann, J.-H., Boschi, C., Brazelton, W.J., Cannat, M., Dunkel, K.G., Escartin, J.,  
915 Harris, M., Herrero-Bervera, E., Hesse, K., John, B.E., Lang, S.Q., Lilley, M.D., Liu, H.-Q.,  
916 Mayhew, L.E., McCaig, A.M., Menez, B., Morono, Y., Quéméneur, M., Rouméjon, S.,  
917 Sandaruwan Ratnayake, A., Schrenk, M.O., Schwarzenbach, E.M., Twing, K.I., Weis, D.,  
918 Whattam, S.A., Williams, M., Zhao, R., 2017b. Expedition 357 methods, in Früh-Green, G.L.,  
919 Orcutt, B.N., Green, S.L., Cotterill, C., and the Expedition 357 Scientists, Atlantis Massif  
920 Serpentinization and Life. Proceedings of the International Ocean Discovery Program, 357:  
921 College Station, TX. <http://dx.doi.org/10.14379/iodp.proc.357.102.2017>.

922 Früh-Green, G.L., Orcutt, B.N., Green, S.L., Cotterill, C., Morgan, S., Akizawa, N., Bayrakci,  
923 G., Behrmann, J.-H., Boschi, C., Brazelton, W.J., Cannat, M., Dunkel, K.G., Escartin, J.,  
924 Harris, M., Herrero-Bervera, E., Hesse, K., John, B.E., Lang, S.Q., Lilley, M.D., Liu, H.-Q.,  
925 Mayhew, L.E., McCaig, A.M., Menez, B., Morono, Y., Quéméneur, M., Rouméjon, S.,  
926 Sandaruwan Ratnayake, A., Schrenk, M.O., Schwarzenbach, E.M., Twing, K.I., Weis, D.,  
927 Whattam, S.A., Williams, M., Zhao, R., 2017c. Eastern sites, in Früh-Green, G.L., Orcutt,  
928 B.N., Green, S.L., Cotterill, C., and the Expedition 357 Scientists, Atlantis Massif  
929 Serpentinization and Life. Proceedings of the International Ocean Discovery Program, 357:  
930 College Station, TX. <http://dx.doi.org/10.14379/iodp.proc.357.103.2017>.

931 Früh-Green, G.L., Orcutt, B.N., Green, S.L., Cotterill, C., Morgan, S., Akizawa, N., Bayrakci,  
932 G., Behrmann, J.-H., Boschi, C., Brazelton, W.J., Cannat, M., Dunkel, K.G., Escartin, J.,  
933 Harris, M., Herrero-Bervera, E., Hesse, K., John, B.E., Lang, S.Q., Lilley, M.D., Liu, H.-Q.,  
934 Mayhew, L.E., McCaig, A.M., Menez, B., Morono, Y., Quéméneur, M., Rouméjon, S.,  
935 Sandaruwan Ratnayake, A., Schrenk, M.O., Schwarzenbach, E.M., Twing, K.I., Weis, D.,  
936 Whattam, S.A., Williams, M., Zhao, R., 2017d. Central sites, in Früh-Green, G.L., Orcutt,  
937 B.N., Green, S.L., Cotterill, C., and the Expedition 357 Scientists, Atlantis Massif  
938 Serpentinization and Life. Proceedings of the International Ocean Discovery Program, 357:  
939 College Station, TX. <http://dx.doi.org/10.14379/iodp.proc.357.104.2017>.

940 Früh-Green, G.L., Orcutt, B.N., Green, S.L., Cotterill, C., Morgan, S., Akizawa, N., Bayrakci,  
941 G., Behrmann, J.-H., Boschi, C., Brazelton, W.J., Cannat, M., Dunkel, K.G., Escartin, J.,  
942 Harris, M., Herrero-Bervera, E., Hesse, K., John, B.E., Lang, S.Q., Lilley, M.D., Liu, H.-Q.,  
943 Mayhew, L.E., McCaig, A.M., Menez, B., Morono, Y., Quéméneur, M., Rouméjon, S.,  
944 Sandaruwan Ratnayake, A., Schrenk, M.O., Schwarzenbach, E.M., Twing, K.I., Weis, D.,  
945 Whattam, S.A., Williams, M., Zhao, R., 2017e. Western sites, in Früh-Green, G.L., Orcutt,  
946 B.N., Green, S.L., Cotterill, C., and the Expedition 357 Scientists, Atlantis Massif  
947 Serpentinization and Life. Proceedings of the International Ocean Discovery Program, 357:  
948 College Station, TX. <http://dx.doi.org/10.14379/iodp.proc.357.102.2017>.

949 Früh-Green, G.L., Orcutt, B.N., Green, S.L., Cotterill, C., Morgan, S., Akizawa, N., Bayrakci,  
950 G., Behrmann, J.-H., Boschi, C., Brazelton, W.J., Cannat, M., Dunkel, K.G., Escartin, J.,  
951 Harris, M., Herrero-Bervera, E., Hesse, K., John, B.E., Lang, S.Q., Lilley, M.D., Liu, H.-Q.,  
952 Mayhew, L.E., McCaig, A.M., Menez, B., Morono, Y., Quéméneur, M., Rouméjon, S.,  
953 Sandaruwan Ratnayake, A., Schrenk, M.O., Schwarzenbach, E.M., Twing, K.I., Weis, D.,

954 Whattam, S.A., Williams, M., Zhao, R., 2017f. Northern sites, in Früh-Green, G.L., Orcutt,  
955 B.N., Green, S.L., Cotterill, C., and the Expedition 357 Scientists, Atlantis Massif  
956 Serpentinization and Life. Proceedings of the International Ocean Discovery Program, 357:  
957 College Station, TX. Northern sites. <http://dx.doi.org/10.14379/iodp.proc.357.106.2017>.

958 Grimes, C.B., John, B.E., Cheadle, M.J., Wooden, J.L., 2008. Protracted construction of  
959 gabbroic crust at a slow spreading ridge: constraints from  $^{206}\text{Pb}/^{238}\text{U}$  zircon ages from Atlantis  
960 Massif and IODP Hole U1309D (30°N, MAR). *Geochemistry, Geophysics, Geosystems*, 9,  
961 Q08012.

962 Holm, N.G., Charlou, J.L., 2001. Initial indications of abiogenic formation of hydrocarbons in the  
963 Rainbow ultramafic hydrothermal system, Mid-Atlantic Ridge. *Earth and Planetary Science*  
964 *Letters*, 191(1–2), 1–8.

965 Ildfonse, B., Blackman, D.K., John, B.E., Ohara, Y., Miller, D.J., MacLeod, C.J., Integrated  
966 Ocean Drilling Program Expeditions 304/305 Science Party, 2007. Oceanic core complexes and  
967 crustal accretion at slow-spreading ridges. *Geology* 35(7), 623–626.

968 Jagoutz, E., Palme, H., Baddenhausen, H., Blum, K., Cendales, M., Dreibus, G., Spettel, B.,  
969 Lorenz, V., Vanke, H., 1979. The abundance of major, minor and trace elements in the earth's  
970 mantle as derived from primitive ultramafic nodules. *Geochimica et Cosmochimica Acta* 11  
971 (2), 2031–2050.

972 John, B. E., Cheadle, M. J., 2010. Deformation and alteration associated with oceanic and  
973 continental detachment fault systems; are they similar? *Geophysical Monograph* 188, 175-  
974 205.

975 John, B.E., Cheadle, M.J., Gee, J.S., Grimes, C.B., Morris, A., and Pressling, N., 2009. Data  
976 report: spatial and temporal evolution of slow spread oceanic crust—graphic sections of core

977 recovered from IODP Hole U1309D, Atlantis Massif, 30°N, MAR (including Pb/U zircon  
978 geochronology and magnetic remanence data). In Blackman, D.K., Ildefonse, B., John, B.E.,  
979 Ohara, Y., Miller, D.J., MacLeod, C.J., and the Expedition 304/305 Scientists, *Proc.*  
980 *IODP*, 304/305: College Station, TX (Integrated Ocean Drilling Program Management  
981 International, Inc.). doi:10.2204/iodp.proc.304305.205.2009.

982 Jørgensen, S.L., Zhao, R., 2016. Microbial Inventory of Deeply Buried Oceanic Crust from a  
983 Young Ridge Flank. *Frontiers in Microbiology* 7:820. doi: 10.3389/fmicb.2016.00820.

984 Karson, J.A., Früh-Green, G.L., Kelley, D.S., Williams, E.A., Yoerger, D.R., Jakuba, M., 2006.  
985 Detachment shear zone of the Atlantis Massif core complex, Mid-Atlantic Ridge, 30°N.  
986 *Geochemistry, Geophysics, Geosystems* 7(6), Q06016.

987 Kelemen, P. B., Dick, H. J., Quick, J. E., 1992. Formation of harzburgite by pervasive melt/rock  
988 reaction in the upper mantle. *Nature* 358(6388), 635-641.

989 Kelemen, P.B., Kikawa, E., Miller, D.J., Shipboard Scientific Party, 2007. Leg 209 summary:  
990 processes in a 20-km-thick conductive boundary layer beneath the Mid-Atlantic Ridge, 14°–  
991 16°N. In Kelemen, P.B., Kikawa, E., Miller, D.J. (Eds.), *Proceedings of the Ocean Drilling*  
992 *Program, Scientific Results, 209*: College Station, TX (Ocean Drilling Program), 1–33.

993 Kelley, D.S., Karson, J.A., Blackman, D.K., Früh-Green, G.L., Butterfield, D.A., Lilley, M.D.,  
994 Olson, E.J., Schrenk, M.O., Roe, K.K., Lebon, G.T., Rivizzigno, P., the AT3-60 Shipboard  
995 Party, 2001. An off-axis hydrothermal vent field near the Mid-Atlantic Ridge at 30°N. *Nature*  
996 412(6843), 145–149.

997 Kelley, D.S., Karson, J.A., Früh-Green, G.L., Yoerger, D.R., Shank, T.M., Butterfield, D.A.,  
998 Hayes, J.M., Schrenk, M.O., Olson, E.J., Proskurowski, G., Jakuba, M., Bradley, A., Larson, B.,  
999 Ludwig, K., Glickson, D., Buckman, K., Bradley, A.S., Brazelton, W.J., Roe, K., Elend, M.J.,

1000 Delacour, A., Bernasconi, S.M., Lilley, M.D., Baross, J.A., Summons, R.E., Sylva, S.P., 2005.  
1001 A serpentinite-hosted ecosystem: the Lost City hydrothermal field. *Science* 307(5714), 1428–  
1002 1434.

1003 Konn, C., Charlou, J.L., Donval, J.P., Holm, N.G., Dehairs, F., Bouillon, S., 2009. Hydrocarbons  
1004 and oxidized organic compounds in hydrothermal fluids from Rainbow and Lost City  
1005 ultramafic-hosted vents. *Chemical Geology* 258(3–4), 299–314.

1006 Lang, S.Q., Butterfield, D.A., Schulte, M., Kelley, D.S., Lilley, M.D., 2010. Elevated  
1007 concentrations of formate, acetate and dissolved organic carbon found at the Lost City  
1008 hydrothermal field. *Geochimica et Cosmochimica Acta* 74(3), 941–952.

1009 Lang, S.Q., Früh-Green, G.L., Bernasconi, S.M., Lilley, M.D., Proskurowski, G., Méhay, S.,  
1010 Butterfield, D.A., 2012. Microbial utilization of abiogenic carbon and hydrogen in a  
1011 serpentinite-hosted system. *Geochimica et Cosmochimica Acta* 92, 82–99.

1012 Lang S.Q., Früh-Green G.L., Bernasconi S.M., Brazelton W.J., Schrenk, M.O., and McGonigle, J.,  
1013 2018. Deeply-sourced formate fuels sulfate reducers but not methanogens at Lost City  
1014 hydrothermal field. *Nature Scientific Reports* 8, 755.

1015 Ludwig, K.A., Kelley, D.S., Butterfield, D.A., Nelson, B.K., Früh-Green, G.L., 2006. Formation  
1016 and evolution of carbonate chimneys at the Lost City hydrothermal field. *Geochimica et*  
1017 *Cosmochimica Acta* 70(14), 3625–3645.

1018 Martin, B. and Fyfe, W.S., 1970. Some experimental and theoretical observations on the kinetics of  
1019 hydration reactions with particular reference to serpentinization, *Chemical Geology* 6, 185-195.

1020 Mason, .U., Nakagawa, T., Rosner, M., Van Nostrand, J.D., Zhou, J., Maruyama, A., Fisk, M.R.,  
1021 Giovannoni, S.J., 2010. First investigation of the microbiology of the deepest layer of ocean  
1022 crust. *PLoS One* 5(11), e15399.

1023 Malvoisin, B., Brunet, F., Carlut, J., Rouméjon, S. & Cannat, M., 2012. Serpentinization of oceanic  
1024 peridotites: 2. Kinetics and processes of San Carlos olivine hydrothermal alteration. *Journal of*  
1025 *Geophysical Research* 117, B04102, doi:10.1029/2011JB008842.

1026 McCaig, A.M., Delacour, A., Fallick, A.E., Castelain, T., Früh-Green G.L., 2010. Fluid  
1027 circulation and isotopic alteration in and beneath oceanic detachment faults in the Central  
1028 Atlantic: Implications for the geometry and evolution of high-temperature hydrothermal  
1029 circulation cells at slow-spreading ridges, In: *Diversity of Hydrothermal Systems on Slow*  
1030 *Spreading Ocean Ridges*, eds PA Rona, CW Devey, J Dymont, BJ Murton, AGU Geophy.  
1031 Mono. Series 188:207-239.

1032 McCaig, A.M., Harris, M., 2012. Hydrothermal circulation and the dike-gabbro transition in the  
1033 detachment mode of slow seafloor spreading. *Geology* 40, 367-370. doi: 10.1130/G32789.1.

1034 McCollom, T.M., 2016. Abiotic methane formation during serpentinization. *Proceedings of the*  
1035 *National Academy of Sciences* 113 (49) 13965-13970; DOI:10.1073/pnas.1611843113.

1036 Méhay, S., Früh-Green, G.L., Lang, S.Q., Bernasconi, S.M., Brazelton, W.J., Schrenk, M.O.,  
1037 Schaeffer, P., Adam, P., 2013. Record of archaeal activity at the serpentinite-hosted Lost City  
1038 hydrothermal field. *Geobiology* 11(6), 570–592.

1039 Morono, Y., Inagaki, F., Heuer, V.B., Kubo, Y., Maeda, L., Bowden, S., Cramm, M., Henkel, S.,  
1040 Hirose, T., Homola, K., Hoshino, T., Ijiri, A., Imachi, H., Kamiya, N., Kaneko, M., Lagostina,  
1041 L., Manners, H., McClelland, H.-L., Metcalfe, K., Okutsu, N., Pan, D., Raudsepp, M.J.,  
1042 Sauvage, J., Schubotz, F., Spivack, A., Tonai, S., Treude, T., Tsang, M.-Y., Viehweger, B.,  
1043 Wang, D.T., Whitaker, E., Yamamoto, Y., and Yang, K., 2017. Expedition 370 methods. In  
1044 Heuer, V.B., Inagaki, F., Morono, Y., Kubo, Y., Maeda, L., and the Expedition 370 Scientists,  
1045 *Temperature Limit of the Deep Biosphere off Muroto*. *Proceedings of the International Ocean*



1046 Discovery Program, 370: College Station, TX (International Ocean Discovery Program).  
1047 <https://doi.org/10.14379/iodp.proc.370.102.2017>

1048 Nicolas, A., 1986. Structure and petrology of peridotites: Clues to their geodynamic  
1049 environment. *Reviews of Geophysics* 24 (4), 875-895.

1050 Nicolas, A., Prinzhofer, A. (1983) Cumulative or residual origin for the transition zone in  
1051 ophiolites: structural evidence. *Journal of Petrology* 24, 188–206.

1052 Niu, Y., 2004. Bulk-rock major and trace element compositions of abyssal peridotites:  
1053 implications for mantle melting, melt extraction and post-melting processes beneath mid-  
1054 ocean ridges. *Journal of Petrology* 45, 2423–2458.

1055 Orcutt, B.N., Bergenthal, M., Freudenthal, T., Smith, D., Lilley, M.D., Schnieders, L., Green, S.,  
1056 Früh-Green, G.L., 2017. Contamination tracer testing with seabed drills: IODP Expedition  
1057 357. *Scientific Drilling* 23, 39–46.

1058 Paulick, H., Bach, W., Godard, M., De Hoog, J.C.M., Suhr, G., Harvey, J., 2006. Geochemistry  
1059 of abyssal peridotites (Mid-Atlantic Ridge, 15°20'N, ODP Leg 209): implications for  
1060 fluid/rock interaction in slow spreading environments. *Chemical Geology* 234, 179–210.

1061 Proskurowski, G., Lilley, M.D., Kelley, D.S., Olson, E.J., 2006. Low temperature volatile  
1062 production at the Lost City hydrothermal field, evidence from a hydrogen stable isotope  
1063 geothermometer. *Chemical Geology* 229(4), 331–343.

1064 Proskurowski, G., Lilley, M.D., Seewald, J.S., Früh-Green, G.L., Olson, E.J., Lupton, J.E., Sylva,  
1065 S.P., Kelley, D.S., 2008. Abiogenic hydrocarbon production at Lost City hydrothermal field.  
1066 *Science* 319(5863), 604–607.

1067 Rouméjon, S., Cannat, M., 2014. Serpentinization of mantle-derived peridotites at mid-ocean  
1068 ridges: Mesh texture development in the context of tectonic exhumation. *Geochemistry,*  
1069 *Geophysics, Geosystems* 15, 2354–2379.

1070 Rouméjon, S., Cannat, M., Agrinier, P., Godard, M. & Andreani, M., 2015. Serpentinization and  
1071 Fluid Pathways in Tectonically Exhumed Peridotites from the Southwest Indian Ridge (62-65  
1072 E). *Journal of Petrology* 56, 703–734.

1073 Rouméjon, S., Früh-Green, G.L., Orcutt, B.N., and the IODP Expedition 357 Science Party,  
1074 2018. Alteration heterogeneities in peridotites exhumed on the southern wall of the Atlantis  
1075 Massif (IODP Expedition 357). *Journal of Petrology*, 2018, 1-29, doi:  
1076 10.1093/petrology/egy065.

1077 Rouméjon, S., Williams, M.J., Früh-Green, G.L., this issue. In situ oxygen isotope analyses in  
1078 serpentine minerals: constraints on serpentinization during tectonic exhumation at slow- and  
1079 ultraslow-spreading ridges.

1080 Schoolmeesters, N., M. J. Cheadle, B. E. John, P. W. Reiners, J. Gee, and C. B. Grimes (2012),  
1081 The cooling history and the depth of detachment faulting at the Atlantis Massif oceanic core  
1082 complex, *Geochemistry, Geophysics, Geosystems* 13, Q0AG12, doi:10.1029/2012GC004314.

1083 Schrenk, M.O., Kelley, D.S., Bolton, S.A., Baross, J.A., 2004. Low archaeal diversity linked to  
1084 seafloor geochemical processes at the Lost City hydrothermal field, Mid-Atlantic Ridge.  
1085 *Environmental Microbiology* 6, 1086–1095.

1086 Schrenk, M.O., Brazelton, W.J., Lang, S.Q., 2013. Serpentinization, carbon, and deep life.  
1087 *Reviews in Mineralogy and Geochemistry* 75 (1), 575-606.

1088 Schroeder, T., John, B., Frost, B.R., 2002. Geologic implications of seawater circulation through  
1089 peridotite exposed at slow-spreading mid-ocean ridges. *Geology* 30(4), 367–370.

1090 Schroeder, T., John, B.E., 2004. Strain localization on an oceanic detachment fault system,  
1091 Atlantis Massif, 30°N, Mid-Atlantic Ridge. *Geochemistry, Geophysics, Geosystems* 5,  
1092 Q11007.

1093 Schwarzenbach E.M., Früh-Green G.L., Bernasconi S.M., Alt J.C, Shanks III W.C., Gaggero  
1094 Laura Crispini, L. 2012. Sulfur geochemistry of peridotite-hosted hydrothermal systems:  
1095 Comparing the Ligurian ophiolites with oceanic serpentinites. *Geochimica Cosmochimica*  
1096 *Acta* 91, 283–305.

1097 Smith, D.K., Cann, J.R., Escartin, J., 2006. Widespread active detachment faulting and core  
1098 complex formation near 13°N on the Mid-Atlantic Ridge. *Nature* 442(7101), 440–443.

1099 Smith, D.K., Escartín, J., Schouten, H., Cann, J.R., 2008. Fault rotation and core complex  
1100 formation: significant processes in seafloor formation at slow-spreading mid-ocean ridges (Mid-  
1101 Atlantic Ridge, 13°–15°N). *Geochemistry, Geophysics, Geosystems* 9(3), Q03003.

1102 Tucholke, B.E., Behn, M.D., Buck, W.R., Lin, J., 2008. Role of melt supply in oceanic detachment  
1103 faulting and formation of megamullions. *Geology* 36(6), 455–458.

1104

1105

1106 **Figures captions**

1107 Figure 1. Bathymetry together with structural and morphological characteristics of the Atlantis  
1108 Massif. (a) 3-D terrain model with a northward view of the detachment fault surface showing  
1109 striations associated with detachment faulting, cross-cutting tectonic structures, with locations of  
1110 the IODP Expedition 357 drill sites, the Lost City hydrothermal field (LC, yellow star) and IODP  
1111 Site U1309. Based on new multibeam bathymetry acquired at 50 m resolution. (b) Interpretation  
1112 of structural and morphological characteristics from new bathymetry data acquired during the  
1113 expedition (reproduced from Früh-Green et al., 2017a).

1114  
1115 Figure 2. Lithologic variations on a regional scale and with depth in cores recovered during  
1116 IODP Expedition 357. Percentages indicate overall percent core recovery for each hole. The  
1117 central sites, highlighted in blue, recovered *in situ* sequences, whereas talus debris was recovered  
1118 at the western and eastern sites along the southern ridge.

1119  
1120 Figure 3. Examples of variations in rock type and structures in IODP Exp. 357 drill cores. (a)  
1121 Serpentinized and oxidized dunite cut by moderately dipping calcite veins (Cc) and fractures  
1122 filled with foraminiferous carbonate sediment (Sed). (b) Relationships between schistose zone  
1123 talc-amphibole-chlorite schists (greenish-white domains) at the contact to cataclastically  
1124 deformed metadolerite (Mdol). (c) Steeply dipping banded serpentine  $\pm$  talc veins cutting  
1125 serpentinized harzburgite. Light grey domains are previous fluid pathways resulting in  
1126 metasomatic replacement of antigorite (Ant) by talc (Tc) (Rouméjon et al., 2018). (d)  
1127 Metasomatic zones of talc-amphibole-chlorite schist (Tc-Amp-Chl) at contact to serpentinized

1128 dunite (Dun) intruded by dolerite and transitioning again to talc-amphibole-chlorite schist.

1129 Photos: IODP ESO.

1130

1131 Figure 4. Characteristic serpentine textures and cross-cutting relationships associated with  
1132 progressive alteration and veining in serpentized harzburgite (example from M0076B-7R1, 43-  
1133 45cm); (a) plane polarized light, (b) crossed polarized light, and (c) schematic representation of  
1134 overprinting relationships. Modified from Früh-Green et al., 2017d, Fig. 7.

1135

1136 Figure 5. Model of the tectono-magmatic evolution and alteration of heterogeneous lithosphere  
1137 at Atlantis Massif. (a) Interpretative cross section showing fluid pathways, metasomatic zones  
1138 and extent of serpentinization (light green shaded region) related to detachment faulting and  
1139 steep normal faults (modified after Boschi et al., 2006a). (b) Detail of <100 m detachment shear  
1140 zone (in red-yellow) characterized by heterogeneous, variably altered and deformed gabbroic and  
1141 peridotite lithologies and with extensive synkinematic metasomatism. The resulting talc-  
1142 amphibole schists enclose lenses of relic, locally less deformed, serpentinite and gabbroic rocks  
1143 (modified from Boschi et al., 2006a). (c) Example of magmatic intrusion in a fully serpentized  
1144 harzburgite from Core M0072-8R2, 0–18 cm. Late metasomatic alteration at the contact between  
1145 the mafic/ultramafic rocks produced white and green talc-amphibole-chlorite assemblages that  
1146 crosscut the previous texture. Chl = chlorite, tc = talc (reproduced from Früh-Green et al., 2017d,  
1147 Fig. 13).

1148

1149 Figure 6. Example of complex lithological and deformation relationships between mafic  
1150 intrusions in peridotite and metasomatic domains in the IODP Expedition 357 cores, showing a

1151 transition from static alteration to strain localization in alternating talc-, amphibole-, and chlorite-  
1152 rich shear zones (from Core M0072B-7R-1, 0–105 cm). Red circles = samples taken for XRD  
1153 analyses and corresponding mineral assemblages. Serp = serpentinite, Mt = magnetite, Ox =  
1154 oxide, Amph = amphibole, Chl = chlorite, Hdx = hydroxide, Zeol = zeolite, Carb = carbonate.  
1155 Modified from Früh-Green et al., 2017d, Fig. 12.

1156

1157 Figure 7. Selected whole-rock major elements (normalized, volatile-free compositions, and in  
1158 weight % oxides, wt %) vs. MgO for serpentinized ultramafic rocks (including impregnated /  
1159 metasomatized samples) and talc-amphibole-chlorite schists from Atlantis Massif, IODP Exp.  
1160 357. Data from Mid-Atlantic-Ridge abyssal serpentinized peridotites and talc-altered peridotites  
1161 are shown for comparison. Talc-amphibole alteration is associated with a general trend to higher  
1162 Si, Ca and Al compositions and a decrease in Mg and Fe. Global abyssal peridotite field defined  
1163 by data from PetDB (<http://www.earthchem.org/petdb>, May 2016). Data for talc-altered  
1164 peridotite field from ODP Leg 209, Hole 1268A (Paulick et al., 2006; also from PetDB).  
1165 Modified from Früh-Green et al., 2017a, Fig. 11.

1166

1167 Figure 8. Ni concentrations (calculated as weight % (wt %) oxides and normalized to volatile-  
1168 free concentrations, plotted on a log scale) vs. Mg# of Atlantis Massif mafic and ultramafic rocks  
1169 from Expedition 357 compared with those from cores recovered at Site U1309 during Integrated  
1170 Ocean Drilling Program Expedition 304/305 (Godard et al., 2009).

1171

1172 Figure 9. MgO/SiO<sub>2</sub> vs Al<sub>2</sub>O<sub>3</sub>/SiO<sub>2</sub> diagram showing variations in bulk rock chemistry and  
1173 changes with Si-metasomatism. Atlantis Massif compositions are also compared with

1174 compositions of serpentinites and talc schists from IODP Site U1309 and from 15°20'N  
1175 recovered during ODP Leg 209 (Paulick et al., 2006) as well as the global data set of abyssal  
1176 peridotites reported in Niu (2004), which define a trend parallel to the terrestrial array (Jagoutz et  
1177 al., 1979). The geochemistry of the Atlantis Massif samples reflects a variety of processes  
1178 including modal mineralogical composition, melt impregnation and multiple phases of  
1179 hydrothermal alteration.

1180

1181 Figure 10. Compilation of chondrite-normalized REE concentrations of Atlantis Massif mafic  
1182 and ultramafic rocks from samples of the IODP Expedition 357 drill cores (see Table 2). Values  
1183 for CI chondrite from McDonough and Sun, 1995.

1184

1185 Figure 11. Highest measured hydrogen and methane concentrations in samples from CTD rosette  
1186 bottom waters acquired before drilling and sensor package Niskin bottles taken by RD2 and  
1187 MeBo after drilling at the Atlantis Massif drill sites during IODP Expedition 357. Dark red  
1188 circles indicate samples from the Lost City (LC) plume.

1189

1190 Figure 12. Example of variations in fluid chemistry during drilling operations and correlations of  
1191 geochemical signatures recorded by the sensor packages on the rock drills from sensor data for  
1192 Hole M0076B, Cores 1R–5R. Elapsed time = time since the start of the sensor package data file.  
1193 Penetration depth (in mm) was reconstructed from drill logs.

1194

1195 Figure 13. Frame-grab photograph from drilling video of bubbles (black arrows) that were  
1196 observed issuing from Hole M0070C and around the drill base during operations at this site, even  
1197 when coring had stopped.

1198

1199 Figure 14. Downhole variations in cell counts from interior portions of whole round cores of the  
1200 basement rock samples (and two sediment (Sed) samples from Hole M0069A) taken onboard  
1201 during IODP Exp. 357. Data from Hole M0074 not included due to extensive damage to this  
1202 short sediment core. The shaded region shows the range of counts below the minimum  
1203 quantification limit (MQL) of  $9.8 \text{ cells cm}^{-3}$ .