The Lost City Hydrothermal Field Revisited

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SINCE THE INITIAL discovery of the Lost City Hydrothermal Field in 2000, there have been significant advances in our understanding of the development and evolution of the field, its chemistry, and the associated biota that is, in part, sustained by abiotically produced methane and hydrogen. Results from an *Alvin* submersible diving program in 2003, supported by the US National Science Foundation (NSF), and from a National Oceanic and Atmospheric Administration (NOAA)-funded Ocean Exploration (OE) expedition in 2005 using the robotic vehicles *Hercules* and *Argus*, show that the Lost City field is characterized by a combination of extreme conditions never before seen in the marine environment. These conditions include venting of basic, 40–91°C, metal-poor hydrothermal fluids with high concentrations of dissolved hydrogen, methane, and other low-molecular-weight hydrocarbons (Kelley et al., 2005; Ludwig et al., 2006a; Proskurowski et al., 2006). The fluid chemistry is driven by fluid-rock reactions in the underlying ultramafic basement at temperatures up to 200°C, which have supported hydrothermal activity for > 40,000 years (Ludwig et al., 2005).

Although visual observations indicate a general paucity of fauna within this novel ecosystem, microbiological communities thrive within the porous, warm interior chimney walls and on their outer surfaces. The sustenance and diversity of these communities are strongly coupled to the chemistry and geology of the field. Organisms related to sulfur-oxidizing, sulfate-reducing, and methane-oxidizing bacteria, as well as methane-producing and methane-oxidizing archaea, are present in the fluids and carbonate chimneys (Brazelton et al., 2006). The diversity of meiofauna living on the spongelike surfaces of the chimneys rivals that of black-smoker systems on the Mid-Atlantic Ridge. These peridotite-hosted biotopes differ significantly from axial, volcanic-hosted vent systems in which carbon dioxide is a dominant volatile species. A major driving force for continued exploration of Lost City vent environments will be the role that peridotite-hosted systems may serve as refugia or stepping-stones for chemosynthetic organisms endemic to vents and seeps, including those hosting symbionts, and those dependant on hydrogen and methane-rich hydrothermal fluids. Fracture zones and associated massifs (mountains), similar in character to the Atlantis Massif system, are ubiquitous seafloor features: just as with black smoker environments, there is no reason to believe that the Lost City Hydrothermal Field is "one-of-a-kind" within the world's ocean (Figure 1).

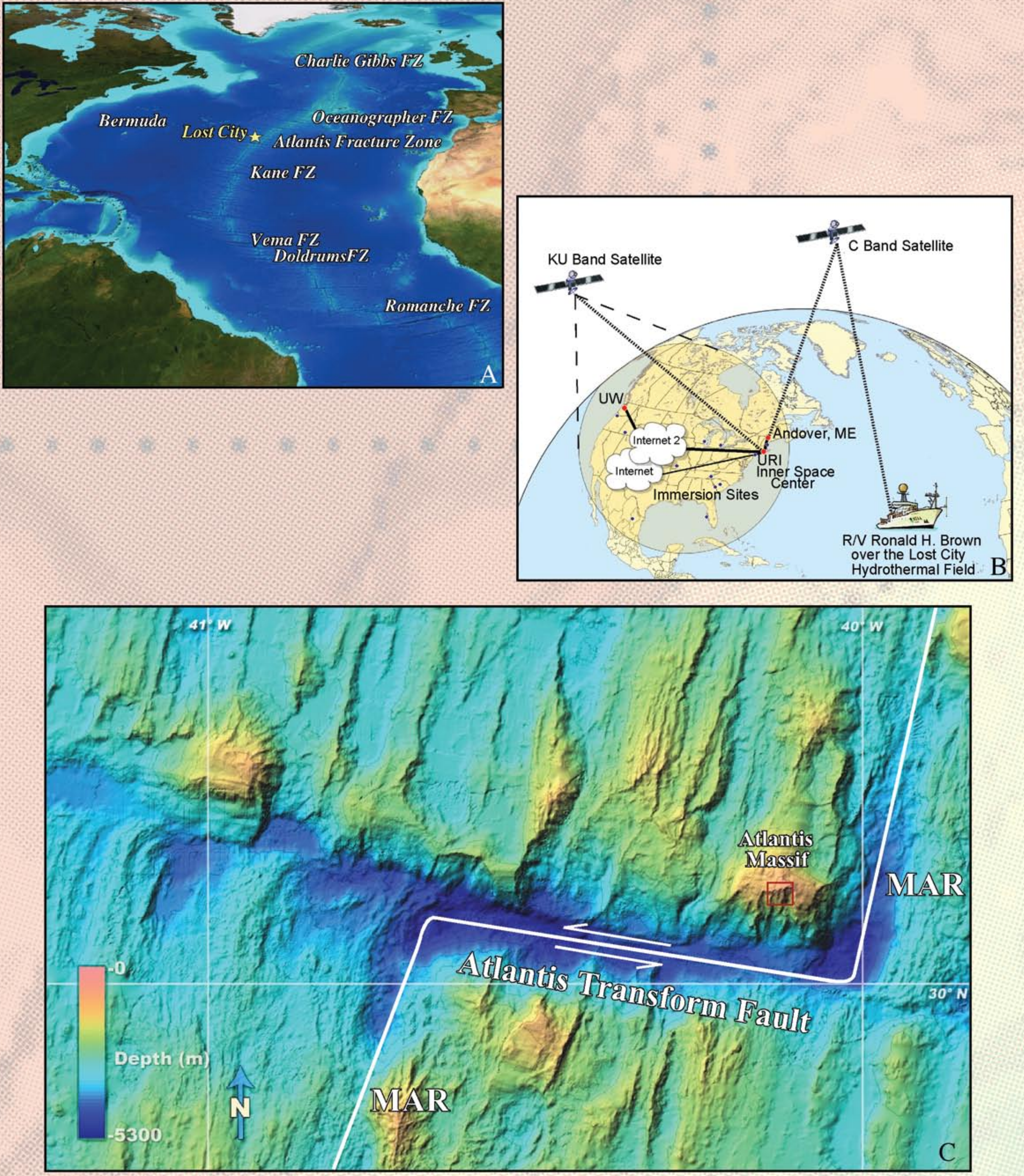

Figure 1. (A) The Lost City Hydrothermal Field is located at 30°N, approximately 15 km west of the Mid-Atlantic Ridge and is bounded to the south by the Atlantis Fracture Zone. Fracture zones are a ubiquitous feature of slow- and ultraslow-spreading systems. This image was generated using the Collaborative Ocean Visualization Environment at the University of Washington. (B) Schematic showing the path of video, voice, and data transmission during the 2005 Ocean Exploration Program. *Image courtesy of Todd Viola, Phil Scheuer, Immersion Presents* (C) Bathymetry of the Atlantis Massif, showing the Mid-Atlantic Ridge (MAR), and the Atlantis Transform Fault. The Lost City Field is located in the area outlined by the red box. Figure 2 shows this area in more detail.

EXPLORING LOST CITY

Since the initial discovery dive at Lost City in 2000 (http://earthguide.ucsd.edu/mar/) (Kelley et al., 2001), there have been two major research expeditions to explore the linkages among geology, hydrothermal flow, and the biology in this novel seafloor ecosystem. In 2003, NSF funded a 32-day expedition using the submersible *Alvin* and the autonomous vehicle *ABE* (http://www.lostcity.washington.edu/). Results from that interdisciplinary cruise included the first detailed bathymetric map of the southern summit of the Atlantis Massif and Lost City field proper (Figure 2), and intense co-registered fluid, rock, and biological sampling of ten of the most significant chimneys within the field (Kelley et al., 2005). The shipboard science team provided live updates during the cruise through the Lost City web site and hosted twelve K–12 schools across the United States and in Zurich, Switzerland (http://www.lostcity.washington.edu/mission/classrooms.html).

In 2005, a 19-day expedition, funded by the NOAA OE program (http://www.oceanexplorer.noaa.gov/explorations/05lostcity/) set a new benchmark for exploration of the ocean. For the first time, this expedition model involved participation of an entire science party housed not on a research vessel, but instead at a Science Command Center at the University of Washington (UW) 4500 miles away from the field; transmission latency was about ~ 1.5 seconds. Twenty-one scientists, graduate students, and undergraduates from across the United States, Japan, and Switzerland conducted their interdisciplinary science around the clock through telepresence at UW.

Data and spectacular video imagery were streamed live from the robotic vehicles *Hercules* and *Argus* via a fiber-optic cable to NOAA's research vessel *Ronald H. Brown* (Figure 1B). From R/V *Brown*, imagery, data, and voice

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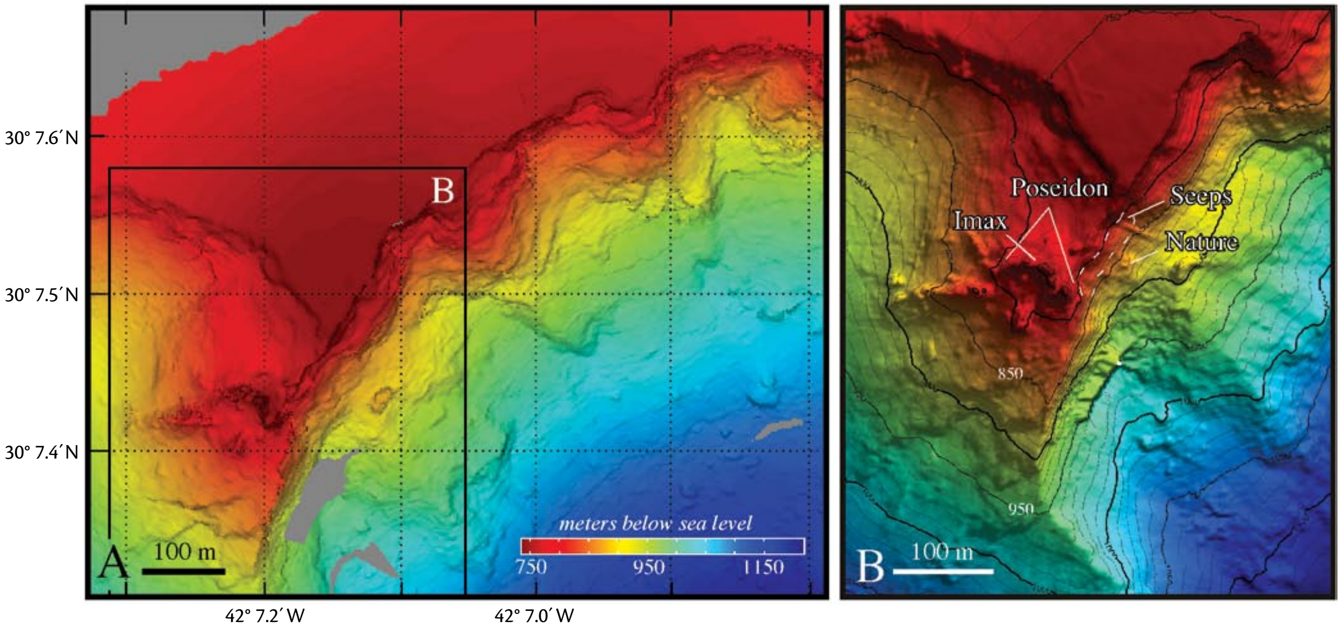

Figure 2. (A) High-resolution bathymetry map of the southern summit of the Atlantis Massif generated by the autonomous vehicle *ABE* during the 2003 expedition. Steep normal faults control mass wasting, which results in the formation of large embayments. Note that the faults do not result in offsets of the carbonate cap rock, indicating that many of them are older features. (B). Detailed bathymetry of the Lost City Hydrothermal Field showing the location of some of the significant carbonate chimneys within the field.

were transmitted to a satellite and on to a downlink station in Maine. From Maine, the signals went to Boston where the data were streamed over Internet2 to the University of Rhode Island's Inner Space Center, to the Science Command Center at UW, and to the University of New Hampshire. The high-definition cameras on both *Hercules* and *Argus* provided unprecedented "eye in the sky" views of the field (Figure 3). During the expedition, there was an intense outreach program through OE, the Jason Project (http://www.jason.org), and Immersion Presents (http://www.immersionpresents.org/), which partnered with the Boys and Girls Clubs of America. During the cruise, 40 half-hour, live, simultaneous broadcasts from R/V *Brown* and UW allowed students to participate virtually on the cruise and to interact live with the science team.

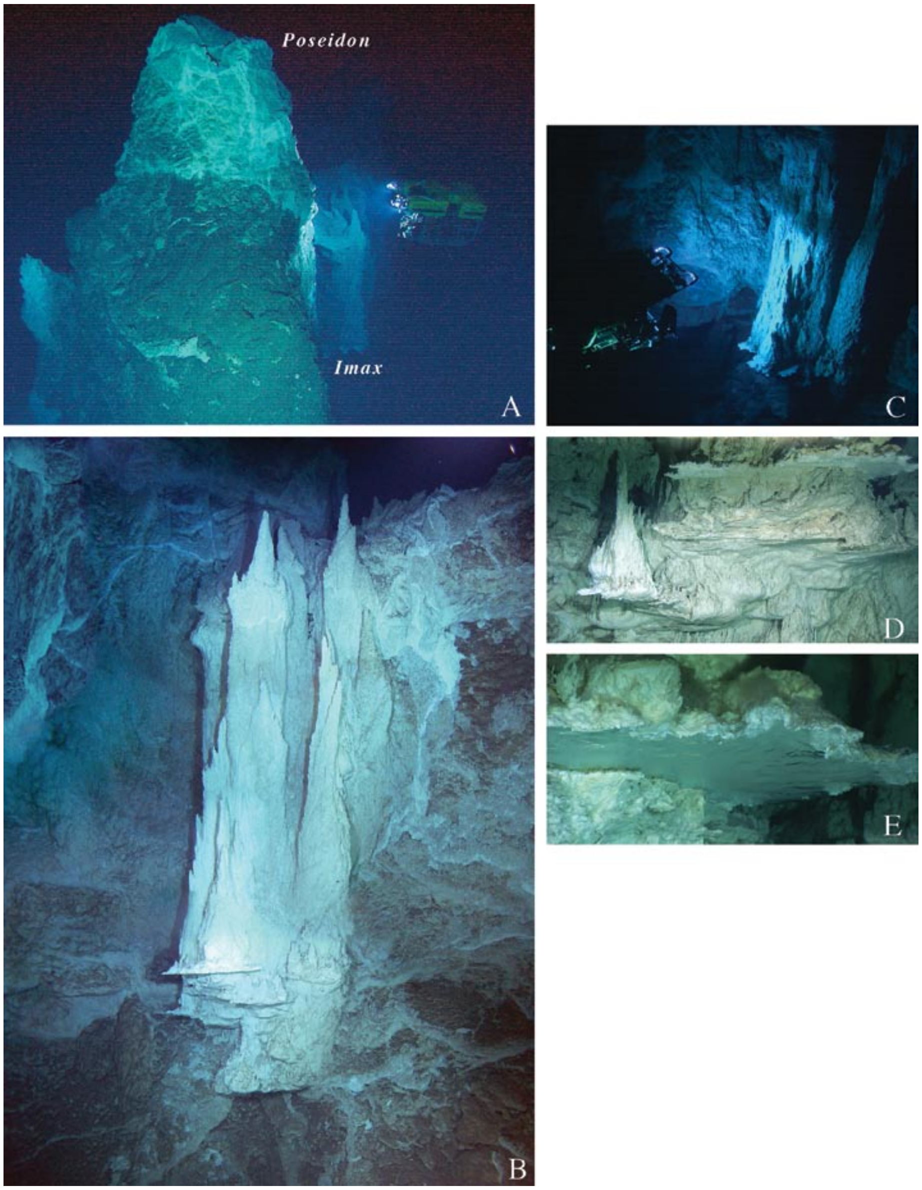

Figure 3. Images of the Poseidon and IMAX structures taken during the 2005 Ocean Exploration Program by the robotic vehicles *Hercules* and *Argus*. (A) The summit of one of four towers that comprise Poseidon. The most active venting occurs near the summit of the tower, as indicated by the formation of white carbonate. This image is looking towards the south at the north face of the complex and shows the three-story-tall parasitic chimney called IMAX. (B) Mosaic of the IMAX tower showing the classic flange deposits that characterize the base of the structure. (C) "Eye in the sky" view of IMAX as *Hercules* approaches. (D) Close-up of the base of IMAX: note reflecting pool of 55°C trapped hydrothermal fluid in upper right corner. (E) Further close-up image of the flange pool shown in the upper right hand portion of D.

MOUNTAINS OF THE DEEP

The Lost City Hydrothermal Field (LCHF) is located on the southern face of the Atlantis Massif near its summit at a water depth of ~ 780 m (Figures 1, 2, and 4). This mountain has formed during the past 1–2 million years through extreme extension and faulting of the oceanic crust during seafloor spreading (Blackman et al., 2002; Karson et al., 2006). The massif is similar in size to continental volcanoes such as Mount Rainer, yet it was formed in the absence of volcanism. A 100-m-thick, gently arched zone of intensely deformed altered rocks extends for > 3 km along the top of the south wall and attests to the importance of crustal attenuation and long-term faulting in formation of the massif (Figure 4) (Boschi et al., 2006b; Karson et al., 2006). Below this sequence, massive exposures of mantle rocks (also called ultramafic rocks because of their high magnesium and iron, and low silica contents) with lesser mafic rocks on the south face of the mountain have a thickness of > 3000 m. Even within this massive zone, there are isolated bands of strongly deformed material that, in turn, have also been cut by later faulting events. The major

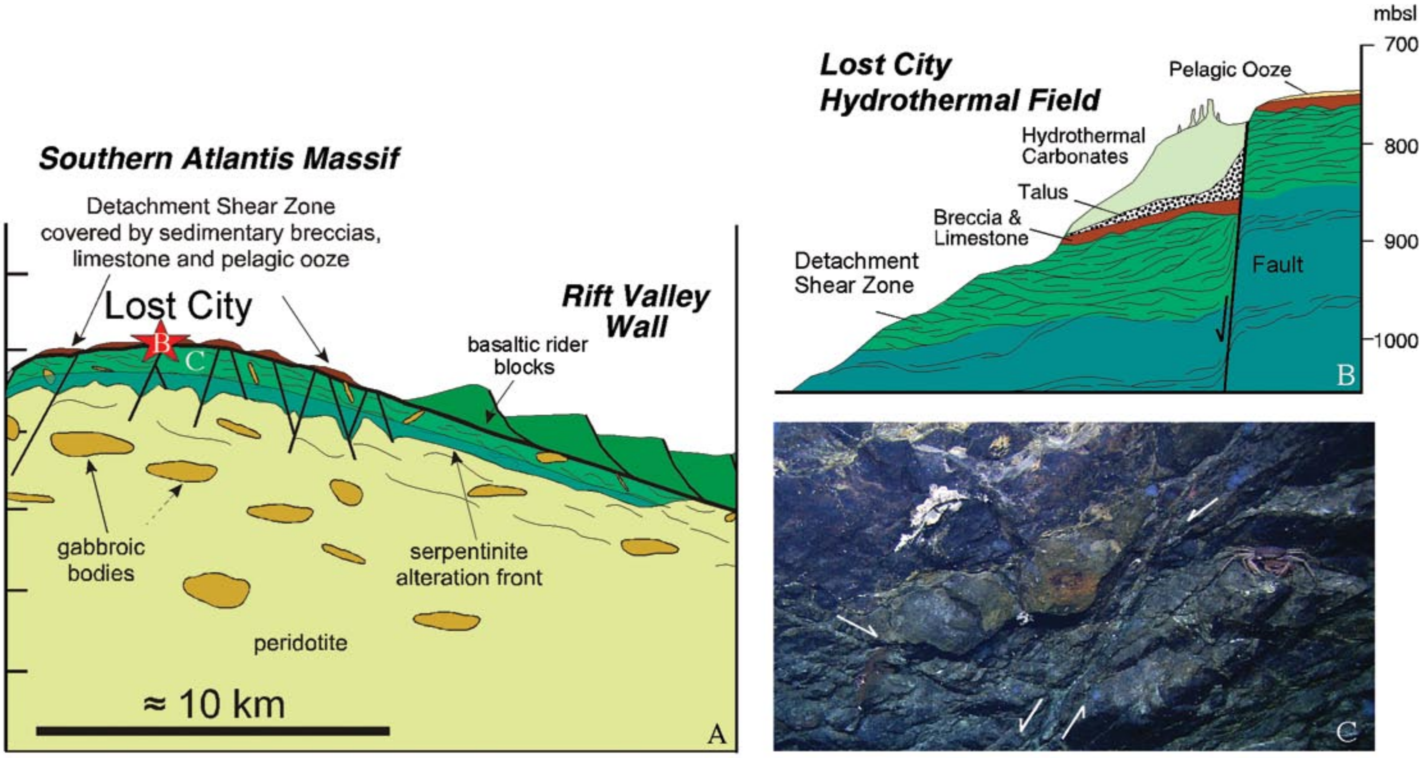

Figure 4. (A) Interpretive cross section of the Atlantis Massif (after Boschi et al., 2006a) showing gabbroic bodies embedded in peridotite and in the detachment fault as well as fluid pathways, metasomatic zones, and the extent of serpentinization (dark and light green). Focusing of fluids along the detachment zone and in discrete shear zones resulted in pervasive alteration of the serpentinites and gabbros. (B) Cross section of the terrace that hosts Lost City (after Karson et al., 2006). The cross section trends northeast-southwest and shows 100-m offset across the northwest trending normal fault that bounds the north side of the field. (C). Highly deformed and faulted serpentinite outcrop that forms the basement rocks ~ 200 m east of the Lost City Hydrothermal Field. Subhorizontal zones of deformation that are cut by subvertical fault networks attest to multiple deformational events in these rocks.

tectonic escarpment provides an unprecedented view of the internal geological structures that comprise the mountain.

The exhumed mafic to ultramafic rocks forming the skin of the south face have undergone intense interaction with circulating hydrothermal fluids. This flow has resulted in pervasive alteration (i.e., 70–100%) and hydration of the mantle rocks and formed serpentinites with attendant remobilization of chemicals during focused flow in the fault zones (Figure 4) (Schroeder and John, 2004; Boschi et al., 2006b; Karson et al., 2006). Oxidizing hydrothermal fluids that penetrated the highly deformed serpentinites to form talc-rich fault rocks (a hydrated magnesium silicate mineral) were enriched in silica, aluminum, calcium, and rare earth elements and were derived by interaction with the gabbroic rocks at temperatures < 500°C (Boschi et al., 2006b). In other zones, high nickel and chromium concentrations and zones dominated by the mineral chlorite (a clay-like, hydrated mineral commonly containing magnesium, aluminum, iron, and silica) may attest to localized mass transfer from the serpentinites to the mafic rocks (Boschi et al., 2006b). Talc, serpentine, and amphibole formation in the rocks that cap the Atlantis Massif may have been of particular importance in its deformation history because these minerals are mechanically weak and therefore may facilitate additional deformation within the fault zone.

Tectonic and hydrothermal processes at LCHF are closely linked and directly influence fluid-flow paths and the chemical and isotopic evolution of the hydrothermal fluids. In addition to the low-angle detachment fault zone that caps the southern portion of the massif, the south face and detachment zone are cut by extensive complex systems of relatively young normal faults (Figure 2). Near the summit of the massif, these faults are central to formation of the field because they serve as conduits that channel hydrothermal flow to the main edifices (Figure 4B). These faults, as well as mass wasting and serpentinization-induced volumetric expansion also enhance exfoliation and penetration of seawater into the basement rocks along the scarp face. High fluid fluxes have significant implications for mass transfer and release and/or uptake of elements, and are recorded by enrichments in B, U, and light REE; by systematic changes in Sr towards seawater values; and by highly depleted bulk rock O-, H-, and B-isotopic compositions in the serpentinized basement rocks (Delacour et al., 2004; Boschi et al., 2006a). High fluid fluxes may particularly impact sulfur and carbon cycles during long-lived hydrothermal circulation. Sulfur geochemistry indicates a loss of primary sulfide, an uptake of seawater sulfate, and local microbial-remediated sulfate reduction and sulfide oxidation in the basement. (Delacour et al., 2005, 2007).

THE LOST CITY FIELD

The Lost City Hydrothermal Field is on a down-dropped terrace on the edge of the south wall of the Atlantis Massif (Figures 1 and 2) (Kelley et al., 2001, 2005; Karson et al., 2006). The surface of the down-dropped block and the summit of the massif are capped by carbonate breccia and hydrothermally cemented pelagic ooze (Figure 4). The difference in depth between these exposures and equivalent outcrops in the upper scarps indicates at least 150 m of vertical displacement on a fault that trends west-northwest. This and faults with similar trends are essentially parallel to the nearby Atlantis Transform Fault (Figure 1C). Thus, the LCHF lies on a structural terrace and is likely situated near the intersection of several relatively large, steeply dipping fault zones on the south wall of the massif.

The intersection of these steeply dipping faults is believed to be the dominant control on upper-crustal permeability that localizes venting in this area. Transform-parallel faults with significant vertical offsets are typical of many other oceanic massifs that have formed near ridge-transform intersections (Lagabrielle et al., 1998; Karson, 1998). The largest and most hydrothermally active structures define an east-west trending linear array more than 200-m long (Figure 2). These observations indicate a systematic and predictable array of permeable pathways that have been active for more than 40,000 years (Früh-Green et al., 2003; Ludwig et al., 2005, 2006a, 2006b).

The core of the field is dominated by the actively venting carbonate monolith called Poseidon, an edifice that rises > 60 m above the surrounding seafloor (Figure 3A). This composite structure forms a massive east-west trending edifice that is ~ 100 m across its base and hosts an array of parasitic chimneys that form flanges and stalactite-like structures that grow from the main trunk. The most impressive of these features is a strikingly beautiful deposit called the IMAX chimney that rises three stories from the north face of Poseidon (Figure 3B and C). This complex structure hosts an array of flanges that trap reflecting pools of 55°C hydrothermal fluid, forming springs that are reminiscent of upside-down waterfalls (Figure 3D and E). The highest temperature fluids in the field vent from an ~ 1-m-tall, beehive-shaped structure on Poseidon that emits pH 10.7 fluids at 91°C. Isolated chimneys are particularly abundant along a narrow rampart that extends nearly continuously to a depth of 1000 m just west of Poseidon.

FORMATION AND EVOLUTION OF THE CARBONATE TOWERS

Five stages define the formation and evolution of the carbonate deposits at Lost City (Ludwig et al., 2006a). The first stage involves the formation of carbonate veins in the serpentinite basement and deposits that grow from fissures in these rocks (Figures 2B and 5). These veins represent the fossilized plumbing system for Lost City. The veins must lace the interior of the southern portion of the massif, whereas the fissures mark a younger, complex array of faulting that cuts both the detachment fault zone and the surface of the massif. Diffuse flow of warm, nutrient-rich fluids from these areas begin to support the development of filamentous bacteria, which may form nucleation sites for precipitation of aragonite and metastable bru-

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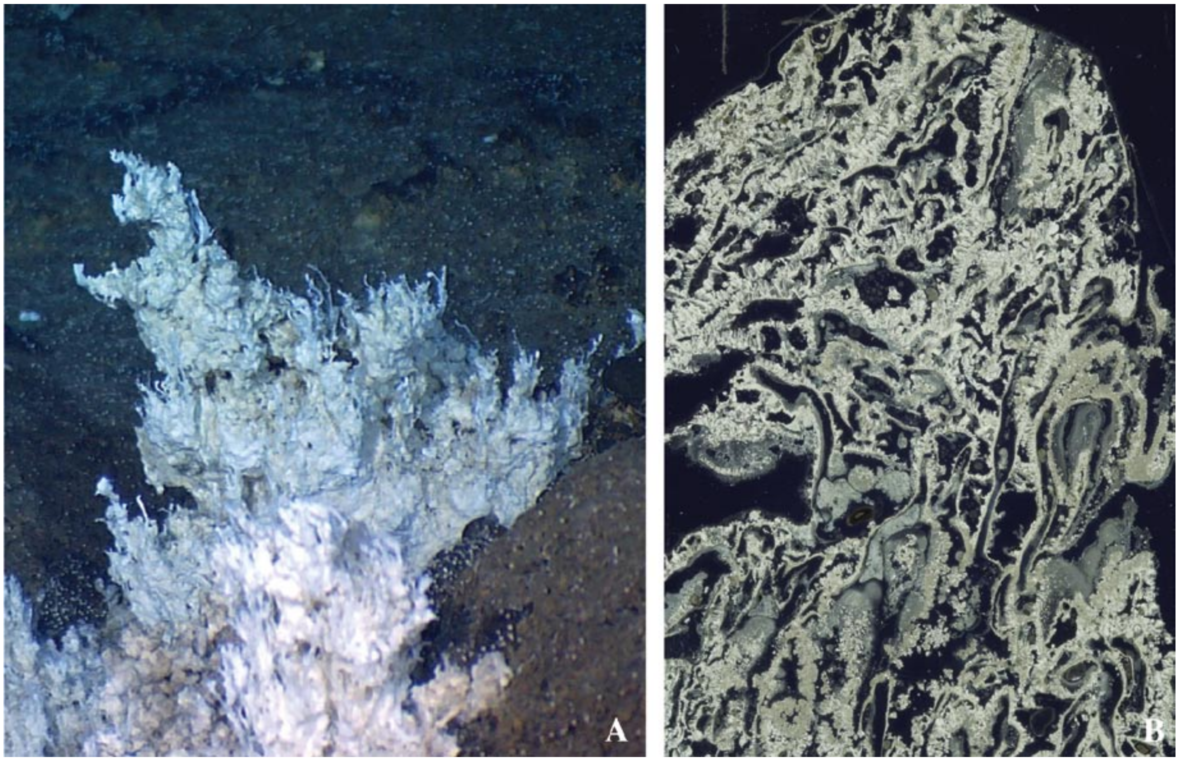

Figure 5. (A) Delicate strands of carbonate form the top of a thicker deposit that is growing from a fissure. The fissure cuts the carbonate caprock at the summit of the Atlantis Massif. This type of deposit typifies the very early stages of chimney development at Lost City. The center deposit is ~ 6 cm high. *Hercules photo* (B) This photomicrograph shows a paper-thin wafer (30 microns) of a young carbonate deposit. The anastomosing nature of the carbonate precipitates is reminiscent of filamentous bacteria that grow on the outside of chimneys awash in hydrothermal-seawater mixtures. The delicate, fine carbonate fingers may represent "fossilization" of filamentous bacteria during nucleation of aragonite crystals on the strands. The development of interlinked pores in the presence of a thermal gradient has recently been suggested to be important as a starting point for the molecular evolution of life (Baaske et al., 2007). Section is ~ 1 cm wide.

cite crystals. Precipitation occurs when the basic hydrothermal fluids mix with carbonate-bearing surrounding seawater (Figure 5). As crystals form, fluid-flow channels become defined, the carbonate deposits grow upward and outward, and friable chimneys begin to form that are also dominated by aragonite and brucite. Typically, these young structures (< 500 years) take the shape of beehive-like cones or flange deposits that trap the highest temperature fluids (Figure 3E) with the lowest magnesium concentrations (<1 mmol/kg).

The third stage of chimney growth is marked by the development of well-defined, sinuous flow channels within the carbonate matrix. As the structures evolve, seawater progressively penetrates the chimney walls, leading to increased precipitation of calcite and an increase in some trace elements (e.g., manganese, titanium, cobalt, vanadium, nickel, and chromium). During these stages, hydrothermal fluids exhibit high pH (9–11), low carbonate alkalinity, and low silica relative to seawater, and elevated Ca concentrations (up to 30 mmol/kg) (Kelley et al., 2005). Because these end-member fluids never archive the extreme high temperatures measured at black-smoker sites, and because they are high in pH, there is a general lack of metals in the fluids (e.g., iron is below detection limit) such that these deposits contain low concentrations of trace elements. Concentrations of methane fall within a narrow range between 1–2 mmol/kg. In contrast, hydrogen ranges from < 1 to 15 mmol/kg, spanning the range for nearly all submarine vents measured (Kelley et al., 2005; Proskurowski et al., 2006). The extreme enrichment of hydrogen with lesser methane is a hallmark of fluid chemistries formed through serpentinization reactions at depths where seawater in contact with olivine oxidizes iron (Janecky and

Seyfried, 1986; Neal and Stanger, 1983; Berndt et al., 1996; McCollom and Seewald, 2001; Foustoukos and Seyfried, 2004). Analysis of hydrogen isotopes in the end-member fluids indicates that methane and hydrogen are produced by serpentinization reactions in the basement rocks at temperatures > 110°C (Proskurowski et al., 2006). Carbon dioxide normally contributed by magmatic sources at mid-ocean ridges is absent or below detection limit in the LCHF fluids (Kelley et al., 2005).

As venting wanes, seawater becomes the dominant determinant of the chimney chemistry. The flow channels begin to fill with fine-grained, micritic calcite that progressively lithifies the chimneys and leads to clogging of some flow channels. Long-term bathing of the outer walls during seawater infiltration results in the conversion of aragonite to calcite, continued trace metal enrichment, and the dissolution of brucite. This transformation is reflected by the chemistry of active structures that contain up to 26 wt% magnesium and calcium concentrations down to 11 wt%, and of extinct structures that typically contain < 1 wt% magnesium and up to 36 wt% calcium. Magnesium in the chimneys is believed to be from seawater because the pure hydrothermal fluids are devoid of this element. During this fourth growth stage, porosity decreases to 30%, and the outsides of the chimneys darken due to precipitation of manganese oxides. Progressive overgrowth of the outer chimney walls during repeated breakout events of hydrothermal fluids leads to fossilization and incorporation of gastropods and foraminifera into the chimney walls. The outer surfaces of the chimneys become progressively rounded and are colonized by corals. Extinct chimneys that are up to 40,000 years old mark the final developmental stage (Ludwig et al., 2006b). These structures have experienced extensive, long-term interaction with seawater and are dominated by calcite. They are massive, dense structures that lack visible flow channels and are brown and commonly knobby in appearance. Because of long-term interaction with seawater, these chimneys contain the highest concentrations of titanium, manganese, and strontium.

LIFE IN HIGH-pH SYSTEMS

Microbial life within the Lost City system is tightly coupled to chimney evolution. Carbonate chimneys bathed in warm, volatile-rich, high-pH fluids harbor high densities of microbes (nearly 10^8–10^9 cells per gram) and contain high proportions of cells related to methane-cycling archaea (Schrenk et al., 2004; Brazelton et al., 2006). Phylogenetic analyses of fluids and carbonate material from across the field indicate the presence of organisms similar to sulfur-oxidizing, sulfate-reducing, and methane-oxidizing bacteria, as well as methane-producing and anaerobic methane-oxidizing archaea. The presence of these metabolic groups indicates that microbial cycling of sulfur and methane may be the dominant biogeochemical processes active within this ultramafic-driven environment (Brazelton et al., 2006).

The interior of the chimneys bathed in fluids > 80°C are dominated by a single phylotype of Lost City Methanosarcinales that is found exclusively in the warm interiors of the young chimneys (Brazeton et al., 2006). In contrast, anaerobic methanotrophic archaea (ANME-1) are restricted to cold, inactive, or weakly venting sites, suggesting that ecological succession occurs in the microbial community as the carbonate chimneys cool down. A hyperthermophilic habitat beneath the LCHF may be reflected by 16S rRNA gene sequences belonging to *Thermococcales* and novel, uncultured *Crenarcharota* identified in the vent fluids. The finding of a diverse microbial ecosystem supported by the interaction of moderate temperature, high-pH fluids resulting from serpentinization reactions in the subsurface provides insights into the biogeochemistry of what may be a pervasive process in ultramafic environments.

Macrofaunal Communities

Vent-endemic habitats of the field are relegated to the hydrothermally active portions of the nearly vertical and porous carbonate edifices, flanges, and spires (~ 10–40°C) (Kelley et al., 2005). They are dominated by several species of gastropods and amphipods. The friable flanges and spires host numerous species of polychaetes, nematodes, euphausids, foraminifera, ostracods, stomatopods, and demosponges. Nonventing habitats are dominated by known deep-sea fauna: *Lophelia*, gorgonian, and *Desmophyllum* corals, galatheid crabs, gastropods, foraminifera, pteropod shells, urchins, asteroids, limpets, ophiuroids, and deep-sea barnacles. The mobile megafaunal component of the Lost City vents includes wreckfish, cut-throat eels, and Geryonid crabs. A surprising discovery regarding animal communities at Lost City is that even though this system appears to host a low biomass, it supports as high if not higher species diversity than *any other* Mid-Atlantic Ridge axial hydrothermal vent site (Kelley et al., 2005).

ARE OTHER LOST CITIES OUT THERE?

Within contemporary oceanic crust, there is a diverse array of submarine environments affected by ongoing serpentinization reactions. These areas include, but are not limited to, the Mariana forearc (Fryer et al., 2000; Mottl et al., 2003), the Arctic (Edmonds et al., 2003) and Antarctic (Dick et al., 2003) ridges, Southwest Indian Ridge and Mid-Atlantic Ridge spreading networks (Gracia et al., 2000; Charlou et al., 2002), major transform faults (Karson, 1998), and highly extended rifted margins (Perez-Gussinye and Reston, 2001; Reston et al., 2001). Any of these tectonic settings could host Lost City-type ecosystems. The abundance and distribution of Lost City-type environments are presently unknown, but it is likely that they are common along or adjacent to a significant portion of the global mid-ocean system. Extensive, uplifted bathymetric features with abundant serpentinite (similar to the Atlantis Massif) associated with extreme crustal attenuation appear to be ubiquitous adjacent to, and far off, axis with respect to mid-ocean ridge spreading centers (Figure 1). Just as with the initial discovery of black-smoker systems, a major driving force for continued exploration of Lost City environments will be determining the role of peridotite-hosted systems as refugia or stepping-stones for chemosynthetic organisms endemic to vents and seeps, including those hosting symbionts, and those dependant on hydrogen- and methane-rich hydrothermal fluids. In addition, the discovery of seafloor hydrothermal ecosystems such as Lost City that do not require magmatic heat may have important implications in our search for life on other differentiated, tectonically active planets or in systems where ultramafic rocks have been exposed through meteorite-impact events (Russell and Hall, 1999; Segura et al., 2002). The certainty that water exists, and has existed, on Mars where there is good evidence for ultramafic rocks (Head et al., 1999; Titus et al., 2003), and the presence of a liquid ocean on Europa (Kivelson et al., 2000) raises the question of whether systems similar to LCHF may be present (or have once been present) elsewhere in the solar system as well. However, for over three decades we have explored the mid-ocean ridge systems, and only one Lost City has yet been discovered. Therefore, it is likely that new Lost Cities will only be found through dedicated discovery programs such as that supported by the NOAA Ocean Exploration Program.

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