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Cold seeps associated with a submarine debris avalanche deposit at Kick'em Jenny volcano, Grenada (Lesser Antilles)

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A B S T R A C T

Remotely operated vehicle (ROV) exploration at the distal margins of a debris avalanche deposit from Kick'em Jenny submarine volcano in Grenada has revealed areas of cold seeps with chemosynthetic-based ecosystems. The seeps occur on steep slopes of deformed, unconsolidated hemipelagic sediments in water depths between 1952 and 2042 m. Two main areas consist of anastomosing systems of fluid flow that have incised local sediments by several tens of centimeters. No temperature anomalies were observed in the vent areas and no active flow was visually observed, suggesting that the venting may be waning. An Eh sensor deployed on a miniature autonomous plume recorder (MAPR) recorded a positive signal and the presence of live organisms indicates at least some venting is still occurring. The chemosynthetic-based ecosystem included giant mussels (*Bathymodiolus* sp.) with commensal polychaetes (*Branchipolynoe* sp.) and cocculinid epibionts, other bivalves, Siboglinida (vestimentiferan) tubeworms, other polychaetes, and shrimp, as well as associated heterotrophs, including gastropods, anemones, crabs, fish, octopods, brittle stars, and holothurians. The origin of the seeps may be related to fluid overpressure generated during the collapse of an ancestral Kick'em Jenny volcano. We suggest that deformation and burial of hemipelagic sediment at the front and base of the advancing debris avalanche led to fluid venting at the distal margin. Such deformation may be a common feature of marine avalanches in a variety of geological environments especially along continental margins, raising the possibility of creating large numbers of ephemeral seep-based ecosystems.

1. Introduction

Kick'em Jenny is the only known active submarine volcano in the Caribbean Sea and has erupted 12 times since it was first recognized in 1939 (Devine and Sigurdsson, 1995; Lindsay et al., 2005). Most eruptions have been explosive and the dominant magma types are hornblende-bearing basalts and basaltic andesites. Multibeam bathymetric surveys conducted in 2002 and 2003 revealed the presence of a prominent arcuate scarp that was identified as the headwall of a major debris avalanche event from an ancestral Kick'em Jenny volcano rising as much as 300 m above sea level (Dondin et al., 2012). Remotely operated vehicle (ROV) exploration of the distal end of the submarine debris avalanche deposit in the backarc Grenada Basin to the west of Kick'em Jenny during cruise NA039 of E/V *Nautilus* has discovered areas of fluid venting similar to methane-based cold seeps found in other nearby marine environments, such as the Barbados forearc accretionary prism (Olu et al., 1997). Here we report on the nature of the venting areas, some preliminary observations of the organisms that inhabit the vents, and propose a model for the formation of the seeps. We suggest that deformation of sediments by the advancing debris avalanche is a likely mechanism for generating ephemeral fluid overpressure at the distal margins of submarine debris avalanches. A similar process may lead to numerous opportunities for the

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development of cold seep ecosystems in other areas of mass wasting such as passive continental margins.

2. Geologic setting

Kick'em Jenny is located approximately 10 km northwest of the island of Grenada and results from the subduction of the Atlantic seafloor beneath the Caribbean plate at a rate of about 2 cm/year (Fig. 1, Wadge, 1984). The volcano has a crater that is approximately 300 m in diameter with the shallowest point located at 190-meters water depth. An active hydrothermal system is currently located in the crater with venting of both gases and fluids up to 230 °C (Olsen et al., 2011). To the west, in the Grenada backarc basin, a large debris avalanche deposit of unknown age has been recognized as far as 14 km from the volcano (Fig. 1). Dondin et al. (2012) suggested that the deposit has a volume of 4.4 km^3 and was generated by the collapse of a pre-existing volcanic island about 200–300 m above sea level, based on the extrapolation of the collapse scar's outer slopes. Finite difference modeling of the avalanche event illustrated that the best simulation of the morphological and runout features occurred with an assumption of Bingham rheology with low Bingham kinematic viscosity and high shear strength (Dondin et al., 2012). The results suggest that the debris avalanche behaved as a stiff, cohesive flow that did not significantly disaggregate during movement downslope.

The Kick'em Jenny debris avalanche deposit differs from other large debris avalanche deposits in the Lesser Antilles by a noticeable lack of discrete angular megablocks (e.g. Deplus et al., 2001; Le Friant et al., 2004). Instead, the Kick'em Jenny avalanche deposit is characterized by irregular subdued hummocky topography with a distinct steep-sided terminus zone at a distance of about 14 km from the volcano. This may be related to a high abundance of pyroclastic material in the slumped mass from the ancestral Kick'em Jenny (e.g. Deplus et al., 2001).

3. Methodology

Bathymetric mapping of the Kick'em Jenny debris avalanche area was done with a Kongsberg EM302 multibeam echosounder system on the E/V *Nautilus* during cruise NA039 in November of 2013. Remotely operated vehicle (ROV) exploration of the distal part of the debris avalanche was also carried out during cruise NA039 using the 2-vehicle system, *Hercules*/*Argus* with a 4000 m depth capability. Water column seep plumes were measured using a pair of NOAA/PMEL Miniature Autonomous Plume Recorders (MAPRs), which include optical backscatter and oxidation–reduction-potential (ORP) sensors (Walker et al., 2007). One MAPR was continuously mounted ~2 m above the lowest base member of the ROV, and the other was mounted either 50 m above the ROV on the telemetry cable (Dive H1322) or directly to a manipulator arm (Dive H1324).

4. Results

4.1. Cold seep morphology

ROV exploration during cruise NA039 initially focused on the identification and sampling of avalanche material in the Kick'em Jenny debris field (Fig. 1). Dive transects revealed an undulating surface of fine-grained hemipelagic sediment with occasional exposures of stratified unconsolidated sediment. As the distal margin of the deposit was approached, the bathymetry became progressively more rugged with vertical cliffs up to 30 m high consisting of relatively flat-lying sequences of highly-stratified hemipelagic sediments. Two main areas of fluid seeps were discovered in this region during dive H1322 (Fig. 1). The areas were roughly 20 by 40 m (Area 1, 12.33601°N/61.72913°W, 1952 m) and 20 by 40 m (Area 2, 12.34946°N/61.72153°W, 2042 m). Both occurred on relatively steep slopes with the source of venting located at the top of small, localized ridges with flow generally terminating at the base of the slope. The pattern of flow was highly channelized and emanated from multiple locations (Fig. 2). No active flow was observed, but the channels had clearly incised the background sediment up to 10 cm in depth. The channels were strongly contrasting in color from white to black as a result of white bacterial mats growing on dark-colored sediment (Fig. 2). Temperature probes taken in both areas at several centimeters below the sediment surface showed no anomalies relative to ambient seawater. However, a negatively buoyant ORP plume was detected at both cold seep sites,

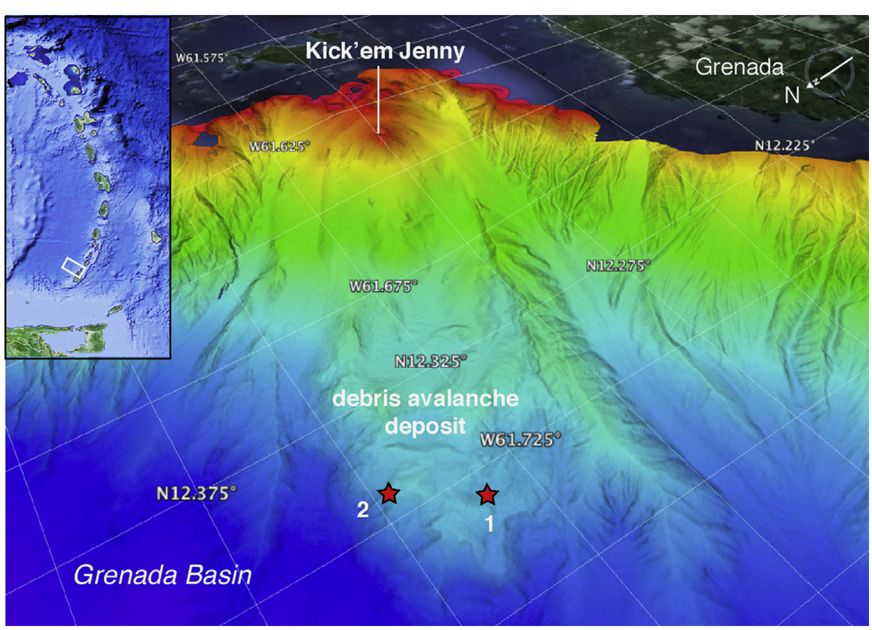

Fig. 1. Map of the southern Lesser Antilles region showing the location of Kick'em Jenny submarine volcano. Bathymetry is from a multibeam survey on cruise NA039. A horseshoe-shaped collapse scar surrounds the cone of Kick'em Jenny and opens to the west toward the Grenada back-arc basin. Stars indicate the locations of the two cold seep areas at the distal end of the Kick'em Jenny debris avalanche deposit. Inset map shows the Lesser Antilles arc with the location of the study area marked by a white box.

Fig. 2. Photomosaic of cold seep Area 2 on the distal end of the Kick'em Jenny debris avalanche deposit in the Grenada Basin. See Fig. 1 for location. Image area is approximately 20 × 40 m and the depth range varied from 2035 to 2050 m.

indicating a mass of chemically-altered seawater that is continuously flowing downslope of the sites in a southerly direction. Plumes were detected as far as 500 m from the epicenter of each seep but remained within 70 m of the seafloor. Given the close proximity of the seeps to each other, a total plume area of roughly 300 m × 1500 m is estimated in the region of discovery. The maximum ORP voltage differential was 70 mV when compared with background signals measured at similar depths away from the seeps. A distinct layer of optical backscatter was also associated with the ORP plume signal.

4.2. Cold seep organisms

At the first seep area (Fig. 1), small zones of macrofaunal communities occurred within the flow channels together with abundant white bacterial mats. Biodiversity consisted mainly of polychaetes (including Siboglinidae (vestimentiferan) tubeworms), holothurians, crabs, some small fish, and one octopus and dead clams. One area of dead clams was clustered around a small whitish-brown outcrop that appeared to be cemented carbonate. The second seep area (Fig. 1) was more extensively colonized and macrofauna included live mussels, cocculinid limpets, clams, gastropods, brittle stars, anemones, holothurians, shrimp, polychaetes (including Siboglinidae tubeworms), crabs, fish, and one octopus (Fig. 3). Zones of abundant mussels and other macrofauna were generally narrow (< 1 m width) and aligned perpendicular to the bedding slope. Of particular interest at the second site was the large number of live giant mussels with commensal scale worms. Based on gross morphology and known species in the region, the mussels are most likely *Bathymodiolus boomerang* or *Bathymodiolus heckerae*, although the seep site is a little shallower than the known *B. heckerae* distribution in the Gulf of Mexico (von Cosel and Olu, 1998; Baptiste et al., 2014). It may also be a recently discovered new species in the Gulf of Mexico that has a similar morphology and depth range to both *B. boomerang* and *B. heckerae* (Baptiste et al., 2014). Detailed genetic work on samples collected during cruise NA039 is in progress and should yield precise species identification of the mussels. Bathymodiolins are the World's largest known mussels (maximum known length 36 cm) and the maximum size of a specimen recovered on

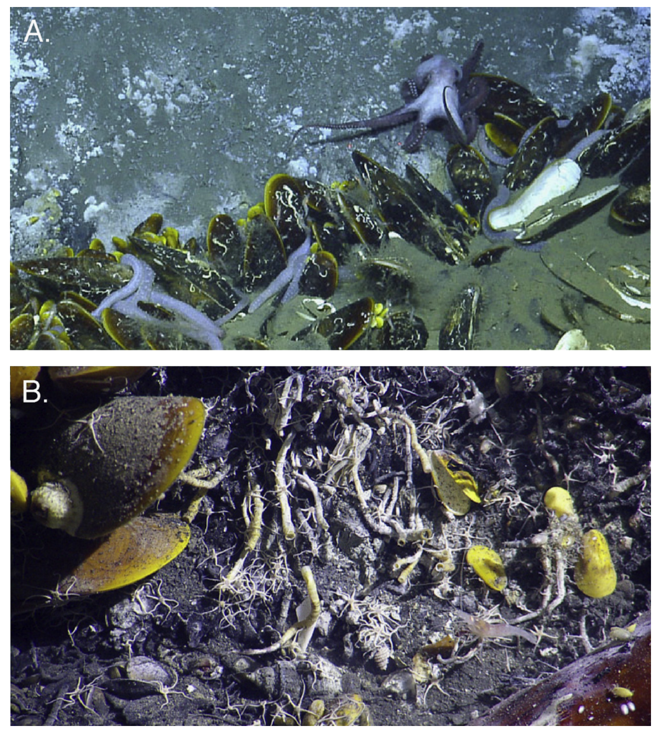

Fig. 3. Chemosynthetic biological communities at cold seep Area 2 on the Kick'em Jenny debris avalanche deposit with (A) giant mussels (*Bathymodiolus* spp.), holothurians, and octopus. Red laser dots near center of image are 10 cm apart. See Fig. 1 for location. (B) Close-up of vent community at seep Area 2 with mussels, tubeworms, brittle stars, gastropods and shrimp. Water depth is 2042 m in both image areas. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 4. Specimen of the giant mussel *Bathymodiolus* spp. collected from cold seep Area 2 at a water depth of 2042 m.

NA039 was 34 cm in length (Fig. 4). Their large size may be attributed to their great longevity in a chemosynthetic environment whose duration spans centuries or more (the age of the Kick'em Jenny ecosystem is unknown), in combination with high growth rates when venting conditions are favorable.

5. Discussion

5.1. Generation of cold seeps at debris avalanche margin

Cold seeps and their associated chemosynthetic communities have been recognized in a variety of geological environments including forearc accretionary prisms (e.g. Olu et al., 1997; Kulm et al., 1986, Wiedicke et al., 2002), near subsurface diapirs in faulted petroleum basins (e.g. Kennicutt et al., 1988), and at zones above methane venting along continental margins (Sibuet and Olu, 1998; Judd et al., 2002; MacDonald et al., 2003; Brothers et al., 2013). To our knowledge they have not been previously described on submarine debris avalanches in volcanic environments. However, recent studies have shown that there may be more of a continuum of hydrothermal vent/cold seep systems in volcanically active areas (e.g. Levin et al., 2012). Based on the location of the Kick'em Jenny cold seeps within the debris avalanche deposit in the Grenada Basin we suggest that they may be related to fluid overpressure generated by deformation of soft hemipelagic sediments by debris avalanche material descending into deeper water following collapse of the ancestral Kick'em Jenny volcano. Dondin et al. (2012) proposed that the debris avalanche was highly cohesive in order to explain the relatively limited runout and the morphologically distinct distal edge. As the debris avalanche flowed from relatively shallow water into the deeper parts of the Grenada Basin it would have encountered soft unconsolidated hemipelagic sediment and likely buried some of it and deformed other parts at the flow front. The position of one of the cold seeps (Area 2) corresponds with an area of high resistive stress (ca. 6×10^7 Pa) identified by Dondin (2010) at the distal part of the deposit in their preferred numerical collapse model. This area was interpreted as a zone of strong deceleration where intense interaction between the lower part of the flow and the substratum (i.e. incorporation, injection) would have occurred. Such strong deceleration may have also triggered fragmentation within the flow front favoring the circulation of pressurized fluid expelled by the substratum due to its rapid burial (i.e. loading). Rapid burial of sedimentary sequences has been suggested as a mechanism for generating fluid overpressures that lead to fluid venting and cold seep development (e.g. Dugan and Flemings, 2000). Two-dimensional modeling of the effects of sediment loading on beds with high porosity predict pressure gradients that drive downslope fluid flow that can destabilize the toe of the slope and provide areas of fluid escape and venting. Although of a different scale, the modeling results of Dugan and Flemings (2000) are likely to be relevant to loadings produced by the Kick'em Jenny debris avalanche as long as the geometrical configuration is similar and that there are beds with relatively high porosity. Sediment coring in the southern Grenada Basin has recovered sandy volcaniclastic turbidites interbedded with hemipelagic sediments, confirming the presence of beds with enhanced porosity (Sigurdsson et al., 1980). We suggest that fluid overpressure and dewatering are likely to be common features associated with debris avalanche emplacement around volcanic islands and that these may provide potential sites for transient cold seep development. The same processes may occur in a broad range of marine debris avalanches and slumps in other geological environments such as passive continental margins. Given the high frequency of such processes (e.g. Booth et al., 1993) this raises the possibility that the abundance of cold seeps and associated chemosynthetic communities may be greatly underestimated. We note that Mayer et al. (1988) discovered cold seeps in the deposits from the slope collapse associated with the 1929 Grand Banks earthquake off the Canadian coast. At 3600 m water depth they observed chemosynthetic communities on the crests of linear gravel waves deposited from the passage of the energetic high-concentration turbidity current generated by collapse further upslope. The coarse-grained nature of the deposit may have provided high porosity zones for overpressured fluids from below to escape at the surface.

5.2. Distribution of cold seep communities

The discovery of cold seeps with chemosynthetic communities in the Grenada Basin provides an important opportunity to study the dispersal of seep-specific chemosynthetic organisms in the Atlantic, Caribbean, and Gulf of Mexico regions (e.g. Cordes et al., 2007). Recent studies have identified groupings and similarities between bathymodiolin cold seep mussels collected from the African margin, eastern equatorial Atlantic, and the Gulf of Mexico (Smith et al., 2000; Olu-Le Roy et al., 2007; Cordes et al., 2007; Génio et al., 2008; Baptiste et al., 2014). These studies have raised important questions concerning the relationships between seeps in the “Amphi-Atlantic” region and the mechanisms by which organisms may disperse and colonize seeps over large distances. Similarities between *Bathymodiolus* species in the Lesser Antilles forearc and Gulf of Mexico are in accord with larval transport by prevailing currents through the inter-island passageways of the Lesser Antilles and eventually up into the Gulf of Mexico (e.g. Arellano et al., 2014). The occurrence of bathymodiolins at both the Barbados forearc cold seeps and in the backarc Grenada Basin is not unexpected based on the proximity (450 km) and current direction (easterly) between the two sites and suggests that the Kick'em Jenny seeps may provide a stepping stone for westward migration of bathymodiolins into the Caribbean Sea. In addition, *B. boomerang* has been found to contain both sulfo-oxidizing and methanotrophic bacteria allowing them to utilize either methane or hydrogen sulfide and thus be well adapted to survive in a range of potential fluid compositions (von Cosel and Olu, 1998). If the mussels found at the Kick'em Jenny cold seep site are in fact *B. boomerang*, their presence may provide some insights into the seeping conditions in the debris avalanche. We speculate that the cold seeps associated with debris avalanches may be ephemeral due to the event-specific nature of their origin. Fluid compositions may therefore change rapidly as the fluid overpressures decay, allowing species such as *B. boomerang* to take advantage of these conditions.

6. Conclusions

Cold seeps with chemosynthetic biological communities have been discovered in the Grenada Basin (Caribbean Sea) on the distal end of a debris avalanche from Kick'em Jenny submarine volcano. Two areas, in water depths between 1950 and 2050 m, occur on relatively steep slopes of deformed hemipelagic sediments and show evidence of downslope fluid flow. Macrofauna observed during ROV exploration include dead clams, giant live mussels (*Bathymodiolus* sp.) with commensal polychaetes (*Branchipolynoe* sp.) and cocculinid limpet epibionts on their shells, other polychaetes (including Siboglinidae (vestimentiferan) tubeworms), gastropods, brittle stars, anemones, holothurians, fish, octopods, shrimp, and crabs. No temperature anomalies were detected at the sites, but a distinct oxidation/reduction potential (Eh) signal was recorded near the seafloor at one of the seeps. We suggest that the origin of the seeps may be related to deformation of hemipelagic sediment during emplacement of the debris avalanche deposit and the generation of internal fluid overpressure. Such a process could potentially operate in other geological environments that are prone to catastrophic sediment mass wasting processes such as passive continental margins. Just as the frequency of high temperature hydrothermal vents is likely biased and underestimated by the extent of exploration of submarine volcanic systems, so too may be the distribution of cold seeps. We predict that understanding of these systems will increase as knowledge of their occurrence in different geological environments is expanded.

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