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Asphalt mounds and associated biota on the Angolan margin

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ABSTRACT

Release of hydrocarbons from sediments is important in increasing habitat heterogeneity on deep ocean margins. Heterogeneity arises from variation in abiotic and biotic conditions, including changes in substratum, geochemistry, fluid flow, biological communities and ecological interactions. The seepage of heavy hydrocarbons to the seafloor is less well studied than most other cold seep systems and may lead to the formation of asphalt mounds. These have been described from several regions, particularly the Gulf of Mexico. Here, we describe the structure, potential formation and biology of a large asphalt mound province in Block 31SE Angola. A total of 2254 distinct mound features was identified by side-scan sonar, covering a total area of 3.7 km^2 of seafloor. The asphalt mounds took a number of forms from small (<0.5 m diameter; 13% observations) mounds to large extensive (<50 m diameter) structures. Some of the observed mounds were associated with authigenic carbonate and active seepage (living chemosynthetic fauna present in addition to the asphalt). The asphalt mounds are seabed accumulations of heavy hydrocarbons formed from subsurface migration and fractionation of reservoir hydrocarbons primarily through a network of faults. In Angola these processes are controlled by subsurface movement of salt structures. The asphalt mounds were typically densely covered with epifauna (74.5% of mounds imaged had visible epifauna) although individual mounds varied considerably in epifaunal coverage. Of the 49 non-chemosynthetic megafaunal taxa observed, 19 taxa were only found on hard substrata (including asphalt mounds), 2 fish species inhabited the asphalt mounds preferentially and 27 taxa were apparently normal soft-sediment fauna. Antipatharians (3.6 ± 2.3% s.e.) and poriferans (2.6 ± 1.9% s.e.) accounted for the highest mean percentage of the observed cover, with actinarians (0.9 ± 0.4% s.e.) and alcyonaceans (0.4 ± 0.2% s.e.) covering smaller proportions of the area. Asphalt mounds represent a common and important habitat on several margin systems globally and should be recognised in future environmental assessment and management of these areas.

1. Introduction

Subsurface flows of hydrocarbons play an important role in increasing habitat heterogeneity in the deep sea (Cordes et al., 2009; Cordes et al., 2010; Cordes et al., 2008; Sibuet and Vangriesheim, 2009). Seafloor expressions of hydrocarbon seepage take a great number of forms depending on fluid flow, the constituents of the release and the substratum (Cordes et al., 2009; Pinheiro et al., 2003; Sibuet and Olu, 1998; Sibuet and Vangriesheim, 2009). Cold seeps, typically of lighter hydrocarbons such as methane, may support high biomass communities of microbes, chemosynthetic fauna, including siboglinid tubeworms, bathymodiolid mussels and vesicomyid clams, and heterotrophic fauna (Cordes et al., 2010). Microbial alteration of hydrocarbons and anaerobic methane oxidation in areas of active hydrocarbon seepage can lead to the formation of extensive areas of hard substratum in the form of authigenic carbonates (Formolo et al., 2004; Wallman et al., 1997). Habitat heterogeneity associated with carbonates, other substrata such as gas hydrates (Sibuet and Vangriesheim, 2009), and structure-forming organisms, in turn supports numerous protozoan and invertebrate species (Sibuet and Olu, 1998) that respond to changes in structural complexity, habitat geochemistry, nutrient sources, and interspecific interactions in different ways and at different scales (Cordes et al., 2010). The widespread occurrence of seeps and hard substrata produced by seabed fluid flow along the continental margins provides mechanisms for the broad-scale distribution of species, for example by facilitating genetic exchange across the Atlantic equatorial belt from the Gulf of Mexico to the seeps of the West Nigerian margin (Cordes et al., 2007). The increased habitat complexity and

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connectivity created by cold seeps on deep continental margins exerts a major influence on the abundance and diversity of species at both local and regional scales (Buhl-Mortensen et al., 2010; Cordes et al., 2009; Levin and Dayton, 2009).

Although the natural seepage of oil is less common than that of lighter hydrocarbons, it nevertheless accounts for nearly half of all oil input to the ocean (Kvenvolden and Cooper, 2003). Oil seeps also occur in a range of environments from the continental shelves (Allen et al., 1970; Vernon and Slater, 1963) to continental slopes (Kennicutt et al., 1988a; Kennicutt et al., 1988b) and deep basins (Didyk and Simoneit, 1989; MacDonald et al., 2004). Satellite imagery from the northwest Gulf of Mexico suggests 1900 km^2 of persistent natural oil slicks at the sea surface in that region alone (Hu et al., 2009), with many other seep regions dispersed globally. Oil seeps also typically release large quantities of methane (Kvenvolden and Rogers, 2005), which may support chemosynthetic communities (Valentine et al., 2010).

Despite the importance of oil seeps as sources of hydrocarbons to the ocean and atmosphere, and the large number of seeps that are likely to exist globally, only a small number of seafloor features (for example, mounds, tar flows, calderas) associated with active seepage of oil have previously been described, and preservation in the geologic record seems rare (Valentine et al., 2010). The seepage of heavy hydrocarbons can lead to the formation of asphalt mounds, large structures of solidified asphalt on the seafloor distinct from irregular mats and pools of viscous tar described from coastal (Hornafius et al., 1999) and continental slope (MacDonald et al., 2003) oil seeps (MacDonald et al., 2004). Asphalt mounds have been identified in deep water in the Gulf of Mexico and the Santa Barbara Basin. Asphalt mounds at the Campeche Knolls (MacDonald et al., 2004), in the Gulf of Mexico, are the most thoroughly investigated. These comprise extensive surface deposits of lava-like solidified asphalt emanating from points along the southern rim of a broad, craterlike graben near the crest of a salt dome (MacDonald et al., 2004). The released petroleum forms characteristic subcircular to linear flow structures at the seafloor up to 20 m wide with surfaces that are ‘ropy’ or ‘rough’, similar to magmatic lava flows. After extrusion, the asphalts are then subject to sequential alterations. The viscosity of the heavy petroleum increases and the volume reduces owing to the loss of volatiles. This solidification and subsequent shrinkage leads to the formation of visible cracks in the asphalt surface, followed by fragmentation of the entire deposit (Brüning et al., 2010). Asphalt mounds have also been found in the Gulf of Mexico at two commercial hydrocarbon appraisal and development areas, Puma (Weiland et al., 2008) and Shenzi (Williamson et al., 2008), both near the Sigsbee Escarpment in the Green Canyon Blocks over 600 km to the NNE of the Campeche Knolls. Furthermore, a single photograph was obtained at another asphalt mound in the Gulf of Mexico (Pequegnat and Jeffrey, 1979). All the asphalt mounds identified in the Gulf of Mexico are associated with shallow buried salt structures (MacDonald et al., 2004; Weiland et al., 2008; Williamson et al., 2008). In the Pacific, asphalt mounds were first identified in shallow waters in Santa Barbara County, California, by SCUBA divers (Vernon and Slater, 1963). Further offshore in the Santa Barbara Basin, high-resolution multibeam data (Keller et al., 2007) have revealed extinct asphalt volcanoes of apparently similar form to the asphalt structures described from the Gulf of Mexico (Valentine et al., 2010).

The biological communities associated with asphalt mounds are often extensive and diverse. Asphalt mounds usually seem to attract a non-chemosynthetic epifaunal assemblage living on the solidified asphalt or nearby authigenic carbonate with asphalt inclusions. In some cases there is also a chemosynthetic community, likely driven by microbial oxidisation of hydrocarbons. Microbial films and mats have been found at the Chapopote site in the Campeche Knolls (MacDonald et al., 2004), at Puma (Weiland et al., 2008), and at an asphalt mound site with active methane venting in the Santa Barbara Basin (Valentine et al., 2010). Vestimentiferan tubeworms (cf. *Lamellibrachia* sp.) were common in close proximity to asphalt flows at Chapopote (MacDonald et al., 2004) and at Puma (Weiland et al., 2008), which they colonized by extending the posterior ends of their tubes into sediments beneath the flow edges or into fissures. Large bivalve shells, including the chemosynthetic family Vesicomyidae (cf. *Calyptogena* sp.), were widespread on the sea floor surrounding the asphalt flows and among asphalt pillows and cobbles at Chapopote. Shells and living specimens of chemosynthetic mussels (cf. *Bathymodiolus* sp. and *Solemya* sp.) were found at Chapopote (MacDonald et al., 2004) and associated with a large mound composed of authigenic carbonate at Puma (Weiland et al., 2008). Heterotrophic fauna at Chapopote included galatheid crabs (*Munidopsis* sp.) and shrimp, as well as non-endemic deep-sea fish and invertebrates (*Benthodytes* sp., *Psychropotes* sp., and *Pterasterias* sp.). Crinoids and soft corals were attached to asphalt pillows found farthest downslope from the rim (MacDonald et al., 2004). The Puma and Shenzi asphalt mounds were inhabited by a range of epifaunal suspension feeders, such as gorgonians, that did not appear to rely on chemosynthetic production for nutrition (Weiland et al., 2008; Williamson et al., 2008). The Santa Barbara Basin asphalt mounds appear to harbour a community of non-chemosysnthetic epifauna, such as anemones, crinoids and cup corals, and provide habitat for mobile species, such as squat lobsters (Galatheoidea) and fish, which are similar to the communities of other rocky reef environments throughout much of the Southern California Bight (Valentine et al., 2010). In general, asphalt mounds appear to be an important habitat in the deep sea, providing a source of hard substratum that attracts an apparently large variety of epifauna. In addition, it appears that areas of asphalt extrusion are often associated with chemosynthetic communities living on asphalt mounds or authigenic carbonates. Asphalt mounds are likely to be considerably more widespread than the current limited evidence suggest, particularly in the vicinity of shallow salt structures, and may be important to consider in regional assessments of deep-water biodiversity.

Here, we describe an extensive and hitherto unknown area of asphalt mounds on the continental slope of Angola, West Africa, the first to be reported from the South Atlantic and the eastern Atlantic continental margin. We describe the structure of the mounds and associated carbonate features, and discuss their possible mode of formation, based on extremely high-resolution acoustic data and seafloor images. In addition, we explore the role of these systems in increasing habitat heterogeneity and biodiversity on the west African margin, focussing specifically on the megafaunal communities associated with the mounds and adjacent benthic habitats. Finally, we demonstrate the variation across these unusual hydrocarbon-driven deep-sea habitats caused by different fluid flow conditions.

2. Materials and methods

2.1. Study site

Angolan licence block 31 covers a 5349 km^2 area of seafloor on the eastern edge of the southern Congo fan (Droz et al., 2003; Savoye et al., 2009). To the north of the block is the Congo submarine canyon, which connects with the Congo River (Savoye et al., 2009). An estimated 55×10^6 t $year^{-1}$ of sediment from the Congo River, typically laden with particulate and dissolved organic matter, is deposited on the seabed from surface-derived flux and lateral transport in turbidity flows (Vangriesheim et al., 2009).