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The impact of fluid advection on gas hydrate stability: Investigations at sites of methane seepage offshore Costa Rica

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ABSTRACT

Fluid flow through marine sediments drives a wide range of processes, from gas hydrate formation and dissociation, to seafloor methane seepage including the development of chemosynthetic ecosystems, and ocean acidification. Here, we present new seismic data that reveal the 3D nature of focused fluid flow beneath two mound structures on the seafloor offshore Costa Rica. These mounds have formed as a result of ongoing seepage of methane-rich fluids. We show the spatial impact of advective heat flow on gas hydrate stability due to the channelled ascent of warm fluids towards the seafloor. The base of gas hydrate stability (BGHS) imaged in the seismic data constrains peak heat flow values to ∼60 mW m^{-2} and ∼70 mW m^{-2} beneath two separate seep sites known as Mound 11 and Mound 12, respectively. The initiation of pronounced fluid flow towards these structures was likely controlled by fault networks that acted as efficient pathways for warm fluids ascending from depth. Through the gas hydrate stability zone, fluid flow has been focused through vertical conduits that we suggest developed as migrating fluids generated their own secondary permeability by fracturing strata as they forced their way upwards towards the seafloor. We show that Mound 11 and Mound 12 (about 1 km apart on the seafloor) are sustained by independent fluid flow systems through the hydrate system, and that fluid flow rates across the BGHS are probably similar beneath both mounds. 2D seismic data suggest that these two flow systems might merge at approximately 1 km depth, i.e. much deeper than the BGHS. This study provides a new level of detail and understanding of how channelled, anomalously-high fluid flow towards the seafloor influences gas hydrate stability. Thus, gas hydrate systems have good potential for quantifying the upward flow of subduction system fluids to seafloor seep sites, since the fluids have to interact with and leave their mark on the hydrate system before reaching the seafloor.

1. Introduction

Transport processes and reactions occurring within subduction zones are reflected in various surface geological phenomena, such as volcanic eruptions, earthquakes, and submarine fluid vents and seeps (e.g. Moore et al., 1990; Moore and Vrolijk, 1992; Oleskevich et al., 1999; Tamura et al., 2002). Much of the fluid volume that is transported into the subduction system within sediments and altered oceanic crust eventually makes its way back to Earth's surface through volcanoes and vent sites. This material recycling process has an important influence on the chemical evolution of the sediments, oceans, and atmosphere (Berner, 1994). Fluids and volatiles making the return journey from great depths in the subduction system can pass through gas hydrate-bearing sediments in the shallow sub-seafloor (e.g. Hensen et al., 2004). Therefore, dynamics of the gas hydrate system can help us to understand the return flow of deep fluids.

Gas hydrates are compounds of gas and water that are stable under high pressure and low temperature conditions encountered in continental margin sediments (Shipley et al., 1979; Sloan, 1998). Aside from their importance for understanding fluid flow in subduction settings, they also represent a potential energy resource, since the global gas hydrate reservoir contains a huge amount of methane (Klauda and Sandler, 2005; Milkov, 2004; Soloviev, 2002). There is concern that large-scale destabilisation of hydrate and

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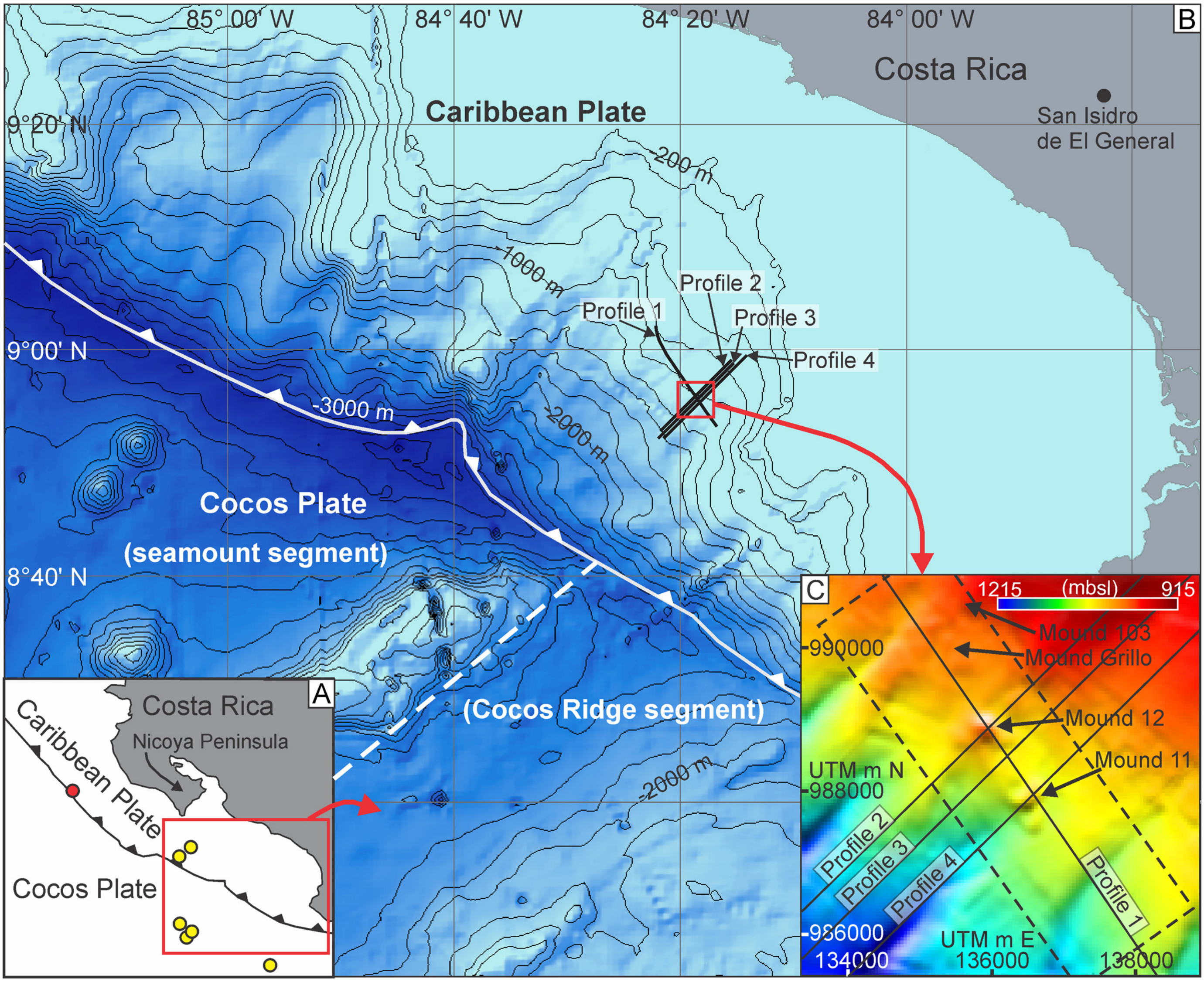

Fig. 1. (**A**) Costa Rica location map showing: north-eastward subduction (toothed line) of the Cocos Plate beneath the Caribbean Plate; CTD cast locations from the NOAA World Ocean Data Atlas (yellow dots); and a CTD cast from Research Cruise SO163-2 (red dot). Red box outlines field of view given in (B). (**B**) Enlargement from (A) showing bathymetry from the General Bathymetric Chart of the Oceans (GEBCO). Red box outlines field of view in (C); black lines in this vicinity are long-offset 2D seismic transects (Profiles 1–4) acquired by R/V Marcus Langseth. Broken white line on the oceanic plate divides the seamount tectonic segment from the Cocos Ridge tectonic segment (nomenclature after von Huene et al., 2000). (**C**) Enlargement from the red box in (B) showing high-resolution bathymetry after Klaucke et al. (2008). Also annotated are the R/V Marcus Langseth seismic transects (labelled solid black lines), the extent of a P-Cable 3D seismic survey acquired in 2010 (broken rectangle), and seafloor mound structures (Mounds 11, 12, 103 and "Grillo"). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

subsequent methane release could reach the atmosphere and contribute to global warming (Berndt, 2005; Kennett et al., 2003). Similarly, methane release into the water column has implications for marine biodiversity, as methane oxidation increases ocean acidity and decreases dissolved oxygen levels (Riebesell, 2008). Also, there is evidence that hydrates may play a role in submarine slope failure (Carpenter, 1981; Crutchley et al., 2007; Pecher et al., 2005; Phrampus and Hornbach, 2012; Sultan et al., 2004).

For all branches of gas hydrate research, there is a need to understand how fluids are being focused into the hydrate stability zone. In terms of hydrate exploitation, these areas are where concentrated deposits are expected to form (Makogon, 2010; Sain and Gupta, 2009). From an environmental perspective, areas of focused fluid flow are often associated with methane seepage into the ocean (Gay et al., 2007; Judd, 2003; Sibuet and Olu-Le Roy, 2002).

Much of our understanding of interactions between focused fluid flow and gas hydrate stability comes from seismic observations of bottom simulating reflections (BSRs), which mark the gas hydrate phase boundary, where gas hydrate is stable above the BSR and free gas is present beneath it (Shipley et al., 1979). This interface is also referred to as the base of gas hydrate stability (BGHS). Disturbances of the hydrate system often manifest themselves as distinct variations in the appearance of BSRs; gas chimneys that penetrate the BGHS, for example, are often accompanied by disruptions of an otherwise continuous BSR (e.g. Gorman et al., 2002; Petersen et al., 2010; Tréhu et al., 2004). Other disturbances are sometimes observed as a shoaling of the BSR, which can indicate locally increased heat flow due to focused fluid flow through the hydrate system (e.g. Pecher et al., 2010; Tréhu et al., 2003; Zwart et al., 1996).

Here, we use 2D and 3D seismic data, as well as geochemical data, to investigate seafloor mound structures offshore Costa Rica (Fig. 1) that have formed as a result of focused fluid flow and gas seepage. Our first aim is to characterise fluid migration pathways beneath the mounds. We pose the question: What are the struc-