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Estimating the time of pockmark formation in the SW Xisha Uplift (South China Sea) using reaction-transport modeling

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ABSTRACT

Carbon cycling and fluid seepage in marine sediments over the late Quaternary were investigated at a now-extinct pockmark located in a mega-pockmark field in the SW Xisha Uplift (NW South China Sea). Measured particulate organic carbon (POC) content, and porewater sulfate (SO_4^{2-}), dissolved inorganic carbon (DIC) concentrations and $\delta^{34}S$-SO_4^{2-} distributions were used to constrain a non-steady-state reaction-transport model and quantify POC mineralization rates as well as estimate the time when fluid flow ceased at the investigated pockmark. An increase in POC content and $\delta^{34}S$-SO_4^{2-} and a decrease in sulfate concentrations in the upper ca. 2 m at the pockmark and a reference core implied an increase in the flux and reactivity of organic matter during the early Holocene around 10 kyr B. P. caused by enhanced primary productivity during the strengthened southwestern summer monsoon. These features were simulated with the model assuming a Holocene increase in POC flux and reactivity. Subsequently, starting from an initial condition reminiscent of a modern active cold seep (Hydrate Ridge), hindcast simulations showed that fluid seepage at the pockmark ceased ca. 39 kyr ago. This corresponds to a relative sea level high-stand, which is believed to be associated with gas hydrate stabilization. The non-steady-state model presented in this contribution can also be used to constrain the time when fluid seepage ceased at other presently extinct cold seeps when suitable sediment and porewater data are available.

1. Introduction

Migration of sediment pore fluid in the seafloor is characteristic of both passive and active continental margins (Judd and Hovland, 2007). The latter are characterized by tectonically driven sediment compaction, faulting and fracturing of the overburden and resulting vertical fluid advection. Advection rates here are assumed to be much greater compared to non-tectonic passive margins (Minshull and White, 1989; Suess et al., 1999; Archer and Buffett, 2012). Despite a lack of continuous tectonic compression, conspicuous features of focused fluid flow have been observed on modern passive margins such as mud volcanoes, pockmarks, hydrate mounds and carbonate slabs (Bouriak et al., 2000; Hustoft et al., 2009a; Wang et al., 2010; Sun et al., 2012b, 2013). Slow upward migration of these fluids, typically enriched in hydrocarbons, creates so called 'cold seeps', which are often regarded as windows to the deep biogeosphere. Cold seeps have guided the exploration of hydrocarbons and support abundant chemosynthetic macrofauna and microbial communities (Heggland, 1998; Hovland and Svensen, 2006; Foucher et al., 2009). In addition, the release of methane from sediments to the water column and, possibly, the atmosphere is of environmental importance because methane is a potent greenhouse gas (Judd et al., 2002; MacDonald et al., 2002). Furthermore, fluid release is also associated with seabed instability (Hovland et al., 2002; Berndt, 2005). Better quantification of fluid flow is thus needed to better quantify carbon emissions from the seafloor.

Pockmarks are among the most common manifestations of fluid flow on the seafloor and are widespread along continental margins (Çifçi et al., 2003; Hovland et al., 2005; Pilcher and Argent, 2007; León et al., 2010). They are seabed depressions of various sizes and morphologies that are generally created either by catastrophic eruption of methane gas or by slow and continuous fluid seepage (Hovland et al., 2002). Discoveries of pockmarks in the northern South China Sea (SCS) have been ongoing as part of exploration of hydrocarbons and gas hydrate reserves (Chow et al., 2000; Wang et al., 2010). Recently, mega-pockmarks (>1000 m in diameter) were documented in the SW Xisha Uplift (NW SCS) and they may have been caused by active fluid flow as well as strong bottom currents (Sun et al., 2011). Geochemical analysis of sediment porewater suggested that the pockmarks are presently inactive and possibly in a quiescent period (Luo et al., 2013). The timing of fluid flow and the widespread development of pockmarks in this area

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remain poorly constrained. Nonetheless, this information is important to understand past fluid flow and its formation trigger mechanisms. The temporal history of paleo-seepage features such as pockmarks could further provide evidence for a possible link between methane release from the seafloor and carbon isotopic excursions in the paleo-climatic record (Dickens et al., 1997; Zachos et al., 2008). Seismic interpretation has been successfully utilized to infer the timing and mechanism of paleo-pockmark formation (Cole et al., 2000; Hustoft et al., 2009b; Andresen and Huuse, 2011; Hartwig et al., 2012; Moss et al., 2012). Isotopic dating of organic carbon, planktonic foraminifera, cold seep fauna, and authigenic carbonates has also been used to elucidate the time of pockmark formation and the historical evolution of fluid seepage (Paull et al., 2002, 2008; Feng et al., 2010; Hill et al., 2012; Taviani et al., 2013).

Our present objective is to understand the timing of pockmark formation in the NW SCS using non-steady-state model approaches (e.g., Mogollón et al., 2012). Hindcast model simulations of a hypothetical fluid seep constrained by geochemical measurements are used to predict the minimum age of the formation of a now-extinct or dormant pockmark in the SW Xisha Uplift. The rates of organic matter degradation and associated biogeochemical processes in pockmarks are also described. The juxtaposition of seepage termination and sea level high-stand leads us to suggest that pockmark activity may be related to variations in the size of the gas hydrate reservoir due to sea level fluctuations.

2. Study area

The northern SCS margin is a passive continental setting bounded to the west by a transform zone toward Indochina and to the east by a subduction zone toward the Philippine arc (Clift et al., 2002; Lüdmann et al., 2005). The study area is located in the SW Xisha Uplift (Fig. 1) with the

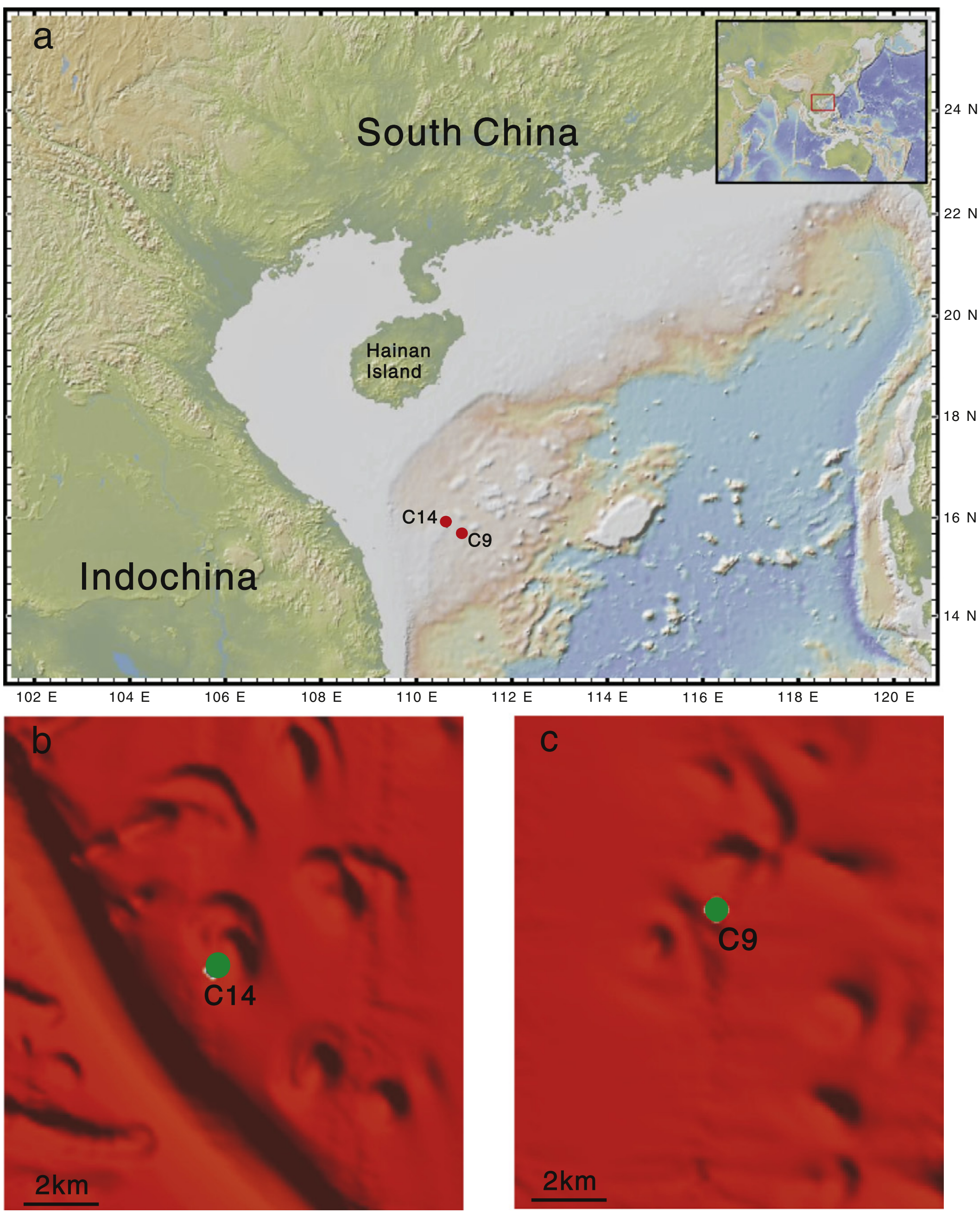

Fig. 1. (a) Map of the study area and sampling sites. The multibeam bathymetric maps in (b) and (c) show the location of the cores relative to the pockmarks.