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Seismic imaging of gas conduits beneath seafloor seep sites in a shallow marine gas hydrate province, Hikurangi Margin, New Zealand

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ABSTRACT

We present recently-acquired high-resolution seismic data and older lower-resolution seismic data from Rock Garden, a shallow marine gas hydrate province on New Zealand's Hikurangi Margin. The seismic data reveal plumbing systems that supply gas to three general sites where seeps have been observed on the Rock Garden seafloor: the 'LM3' sites (including LM3 and LM3-A), the 'Weka' sites (including Weka-A, Weka-B, and Weka-C), and the 'Faure' sites (including Faure-A, Faure-B, and Rock Garden Knoll). At the LM3 sites, seismic data reveal gas migration from beneath the bottom simulating reflection (BSR), through the gas hydrate stability zone (GHSZ), to two separate seafloor seeps (LM3 and LM3-A). Gas migration through the deeper parts of GHSZ below the LM3 seeps appears to be influenced by faulting in the hanging wall of a major thrust fault. Closer to the seafloor, the dominant migration pathways appear to occupy vertical chimneys. At the Weka sites, on the central part of the ridge, seismic data reveal a very shallow BSR. A distinct convergence of the BSR with the seafloor is observed at the exit point of one of the Weka seep locations (Weka-A). Gas supply to this seep is predicted to be focused along the underside of a permeability contrast at the BGHS caused by overlying gas hydrates. The Faure sites are associated with a prominent arcuate slump feature. At Faure-A, high-amplitude reflections, extending from a shallow BSR towards the seafloor, are interpreted as preferred gas migration pathways that exploit relatively-high-permeability sedimentary layers. At Faure-B, we interpret gas migration to be channelled to the seep along the underside of the BGHS — the same scenario interpreted for the Weka-A site. At Rock Garden Knoll, gas occupies shallow sediments within the GHSZ, and is interpreted to migrate up-dip along relatively high-permeability layers to the area of seafloor seepage. We predict that faulting, in response to uplift and flexural extension of the ridge, may be an important mechanism in creating fluid flow conduits that link the reservoir of free gas beneath the BGHS with the shallow accumulations of gas imaged beneath Rock Garden Knoll. From a more regional perspective, much of the gas beneath Rock Garden is focused along a northwest-dipping fabric, probably associated with subduction-related deformation of the margin.

1. Introduction

Gas hydrates are solid structures consisting of gas molecules (usually methane) enclosed by rigid cages of water molecules. The stability of natural gas hydrates is affected mainly by temperature, pressure and pore water salinity (Sloan, 1998), and regional marine gas hydrate provinces are usually defined by identification of a seismic phenomenon known as a bottom simulating reflection (BSR). The BSR marks the base of gas hydrate stability (BGHS), above which conditions are generally favourable for gas hydrate formation, and below which they are not. The BSR is the response to a decrease in seismic velocity and/or density, which is usually attributed to free gas underlying gas hydrate (e.g. Bangs et al., 1993).

Free gas associated with the gas hydrate system can potentially intersect the seafloor at BSR pinch-outs, where the BGHS coincides with the seafloor. Also, in deeper parts of a gas hydrate province, where the BGHS is significantly deeper than the seafloor, free gas can occupy fluid flow conduits and ascend through the regional gas hydrate stability zone (GHSZ) (e.g., at south Hydrate Ridge on the Cascadia subduction margin — Tréhu et al., 2004). A limitation in the availability of water when gas supply exceeds its proportion in hydrate, advection of warm fluids, and the production of hyper-saline pore water by hydrate formation, are possible scenarios allowing migration of free gas through the GHSZ (Ginsburg and Soloviev, 1997; Wood et al., 2002; Liu and Flemings, 2006). The emergence of

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methane gas at seafloor seep sites can be evidenced in numerous ways, for example: higher dissolved methane concentrations in the water column, flares imaged in echograms, video observations of rising gas bubbles, the development of chemosynthetic faunal communities, positive-relief authigenic carbonate mounds, and negative relief pockmarks (e.g. Lewis and Marshall, 1996; Faure et al., 2006; Hovland and Svensen, 2006; Gay et al., 2007; Baco-Taylor et al., 2010-this issue; Faure et al., 2010-this issue; Greinert et al., 2010-this issue; Jones et al., 2010-this issue; Naudts et al., 2010-this issue).

The localised accumulation of free gas in marine sediments often yields anomalous seismic signatures, making seismic methods a useful tool for identification and characterisation of the sub-seafloor ‘plumbing’ beneath seep sites. Gas can manifest itself as both amplitude enhancement and amplitude suppression (e.g. Judd and Hovland, 1992; Gay et al., 2007; Netzeband et al., 2010-this issue), as well as through a disruption of reflections often referred to as “acoustic turbidity” (e.g. Judd and Hovland, 1992; Schroot and Schüttenhelm, 2003; Mathys et al., 2005; Schroot et al., 2005; Gay et al., 2007; Jones et al., 2010-this issue) or in different cases as “disturbed zones” (Schroot and Schüttenhelm, 2003).

Amplitude enhancement of sedimentary or structural features (i.e. “bright spots”) can occur when gas preferentially accumulates in high porosity layers or structural voids such as faults (e.g. Taylor et al., 2000; Tréhu et al., 2004). The result is a marked decrease in acoustic velocity and density (Domenico, 1977), which can yield increased impedance contrasts with adjacent media where gas is not focused and velocity and density remain relatively high.

Amplitude suppression can occur due to physical disruption of sedimentary layering by migrating, gas-charged pore fluids (e.g. Davis, 1992; Gorman et al., 2002), or by highly-reflective overlying interfaces that significantly reduce the transmission of energy (e.g. Judd and Hovland, 1992; Garcia-Gil et al., 2002; Sager et al., 2003). Such highly-reflective overlying interfaces could arise from localised gas accumulations (as mentioned above), or could be due to very hard carbonate formations or concentrated hydrate deposits for example (Behrens, 1988; Reilly et al., 1996; Rollet et al., 2006). Alternatively, amplitude suppression can be caused by absorption and/or scattering of acoustic energy by zones of significant gas concentration (e.g. Judd and Hovland, 1992; Schroot et al., 2005). The term “gas chimney” is widely used to refer to vertical/sub-vertical regions of suppressed reflectivity (e.g. Gorman et al., 2002; Haacke et al., 2008a) or enhanced reflectivity (e.g. Schroot and Schüttenhelm, 2003; Gay et al., 2007) caused by gas. It is also noted, that significant amplitude suppression can be caused by gas hydrates, as preferential growth of hydrate in relatively high porosity sediments can potentially cause amplitude blanking (Dillon et al., 1993; Lee and Dillon, 2001). The chimneys modelled by Liu and Flemings (2007) for example, are predicted to comprise mostly hydrate, with only a few percent of coexisting gas focussed in the centres.

Acoustic turbidity (Hovland and Judd, 1988) refers to a pattern of chaotic reflectivity caused by a scattering of acoustic energy by gas. Judd and Hovland (1992) showed examples from deep-towed boomer data where dark smears in the section obliterate other reflections. Schroot et al. (2005) and Schroot and Schüttenhelm (2003) have correlated regions of acoustic turbidity with zones of amplitude blanking caused by gas, and have also referred to shallow regions of “disturbed reflectivity” that they attribute to the failure of seismic processing to properly image localised areas with anomalously low seismic velocities. Gay et al. (2007) present recent examples of reflection disruption (which they again refer to as acoustic turbidity) that are associated with gas chimneys, bright spots and zones of suppressed reflectivity.

Seep sites are often associated with anomalous seafloor reflectivity (e.g. Anderson and Bryant, 1990; Reilly et al., 1996; Sager et al., 2003; Gay et al., 2007). Free gas in seafloor sediments can significantly reduce density and velocity (Domenico, 1977), resulting in one of two seismic manifestations: 1) a suppressed positive reflection coefficient (when seafloor impedance is decreased but remains higher than that of the water column), or 2) a negative reflection coefficient (when seafloor impedance is lower than that of the water column) (Reilly et al., 1996; Sager et al., 2003). Scenario 2, an extreme case, is more likely to occur in areas of unconsolidated sediments (lower density) and more uniform gas distribution (greater effect on velocity suppression). Strong positive reflection coefficients can arise from hard layers of hydrate or carbonate existing over sufficiently continuous areas of the seafloor (Reilly et al., 1996; Sager et al., 2003).

In this study we present two seismic datasets that reveal gas distribution within the GHSZ of a shallow gas hydrate province known as Rock Garden, part of New Zealand's greater Hikurangi Margin Gas Hydrate Province (Fig. 1). The purpose of the study is to characterise gas migration beneath known seep sites that have been discovered on

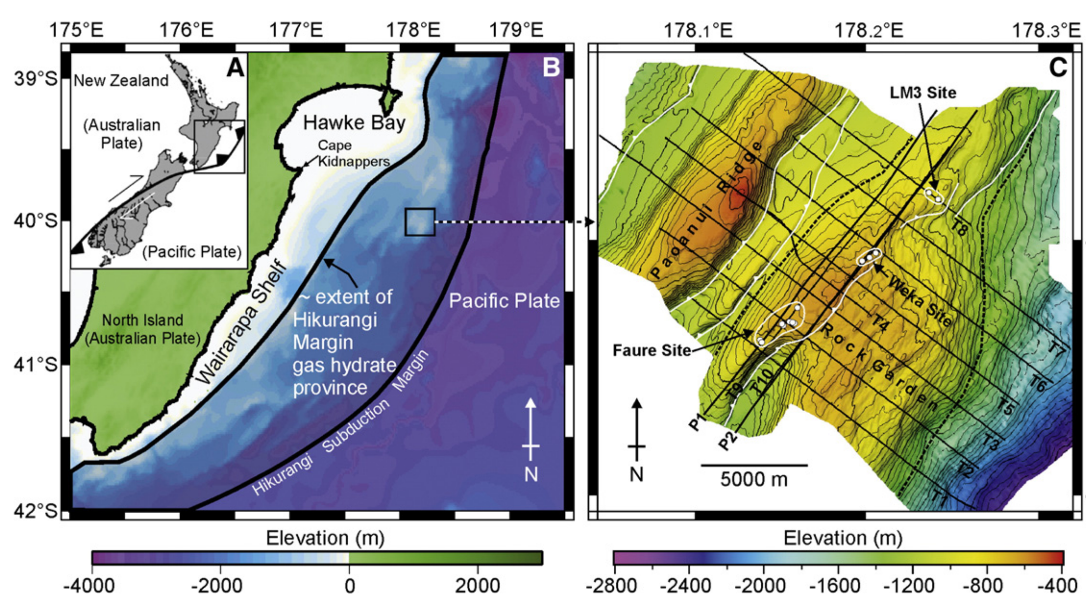

Fig. 1. Location Map, showing: (A) the tectonic setting of New Zealand, (B) the area offshore of the North Island's East Coast, and (C) the Rock Garden area — delineated by the broken black lines. The approximate extent of the gas hydrate province in (B) is after Pecher and Henrys (2003). The eastern extent represents the approximate position of the Hikurangi Subduction Margin. The positions of the seismic lines discussed in this study are shown in (C), as well as the general areas of seafloor seepage (Faure Site, Weka Site, and LM3 Site). Seafloor traces of major thrust faults, including a system that has displaced the Rock Garden ridge top, are also annotated (toothed white lines, after Barnes et al., 2010-this issue).