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Cold seep carbonates and associated cold-water corals at the Hikurangi Margin, New Zealand: New insights into fluid pathways, growth structures and geochronology

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ABSTRACT

The aim of this study is to provide combined new insights into the geochronological framework, isotope geochemical signatures and structural observations of methane related authigenic carbonate settings and associated cold-water corals from offshore New Zealand. The analysed samples are obtained from calcified sediments of three different cold seep areas at the Hikurangi Margin: Opouawe Bank, Uruti and Omakere Ridge. We focused the sub-sampling on aragonitic precipitates in vein like structures, partly still open fluid channel systems and related chemoherm structures in order to identify the timing and signature of focused marine methane emanation. The presented initial U/Th age data set indicates different generations of intensified seep activity and related carbonate precipitation between 12,400 ± 160 and 2090 ± 850 years BP. The youngest stage so far, was identified as contemporaneous cold seep activity at the southernmost (North Tower, Opouawe Bank) and northernmost (Bear's Paw, Omakere Ridge) sampling sites around 2300 years BP. Sharing the same water depth (1050 to 1100 m) these sites imply regional margin-wide tectonic or hydrological changes as controlling process.

An intermediate phase of vein and channel structures within the sediment was detected for a time interval between approximately 5000 and 4000 years BP with contemporaneous settings of focused seep activity around 4300 years BP at Uruti Ridge (LM-10) and Opouawe Bank.

$\delta^{13}C_{PDB}$ data reflect site and carbonate type specific signatures, clustering around −52‰ (Uruti and Omakere Ridge) and −47‰ for the fluid pathway system and the uppermost surface at North Tower site (Opouawe Bank). Late stage precipitates in chemoherm cavities of the latter reflect significantly heavier values of about −38‰. Porous precipitates within open fluid channel systems are characterized by decreased $\delta^{234}U_{(T)}$ values, exceptional high Th and U concentrations and slightly lighter $\delta^{13}C_{PDB}$ signatures when compared to adjacent rim-like and dense cements. This specific kind of precipitate is interpreted as indicator for phases of less vigorous fluid seepage.

The observed occurrence of cold-water corals seems to be mostly depending on the abundance of authigenic carbonates as a substrate exposed to erosive bottom water currents. But, seafloor observations combined with preliminary age data indicate a significant time gap between the inferred end of cold seep activity and coral colonization. U–Th analyses of recent reef-forming coral provided an initial $\delta^{234}U_{(0)}$ value of 146.3 ± 3.9‰ and 0.0013 ± 0.0002 as starting $^{230}Th/^{234}U$ activity ratio for coral growth in the bottom water.

1. Introduction

Authigenic carbonates from cold seeps are potential high-resolution recorder of changes in venting activity and fluid composition through time (e.g. Teichert et al., 2003; Campbell, 2006; Judd and Hovland, 2007); they may or may not be associated with gas hydrates (Teichert et al., 2005). Various examples from modern and ancient cold seeps have been described from continental margins worldwide (e.g. Kulm and Suess, 1990; Campbell et al., 2002, Nymann et al., this issue). After a decade of microbiological and geochemical studies, we know that in marine cold seep environments, methane and other hydrocarbon compounds contained in the ascending fluids are oxidized to bicarbonate (HCO_3^-) by a microbial consortium of sulphate-reducing bacteria and methanotrophic archaea (Boetius et al., 2000). Anaerobic oxidation of methane is the main microbial process driving the precipitation of authigenic carbonate build-ups within subsurface anoxic sediments and the bottom water. This process explains why the seafloor is often cemented by carbonate at sites of active methane seepage, either as chemoherm structures associated to focussed fluid venting that grow into the water column,

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or as carbonate cementations/concretions in the sediment. The lateral and vertical extents of these methane-derived authigenic carbonates are controlled by the balance between the intensity of the fluid flux and the ability of microbes to oxidize methane and reduce sulphate (Luff and Wallman, 2003). The efficiency of this process (Sommer et al., 2006) might not be sufficient enough for high methane flux (in dissolved and especially gaseous phase), so that methane can escape into the water column and may eventually reach the atmosphere (e.g. Sauter et al., 2006). Numerical modelling of carbonate crust formation has shown that bioturbation and sedimentation rates are additional important factors in controlling the flow of water and methane, and thus carbonate precipitation at cold seep sites (Luff et al., 2004).

The carbonate build-ups observed at the seafloor exhibit various morphologies: massive to porous crusts centimeter to meters thick that form large pavements or fragmented slabs, circular chimneys, and irregular concretions corresponding to cemented bioturbation traces. These hard substrates are often inhabited by an abundant motile fauna (bivalves, gastropods, crustaceans, fishes etc.) and colonized by fixed organisms such as tubeworms and cold-water corals, which may become entombed as biotic elements in the seep carbonates (e.g. Campbell et al., this issue).

Mineralogy, geochemical and isotopic signatures of authigenic carbonates depend on the composition of the ascending fluids and the environmental conditions during formation. These studies together with U–Th age constraints on paleo-seepage activity are crucial tools for the identification and understanding of the driving processes, mechanisms and sources of marine methane emanation (Teichert et al., 2003; Kutterolf et al., 2008; Watanabe et al., 2008; Bayon et al., 2009). Cold seep carbonates are in particular suitable for the reconstruction of marine methane emanation and estimates of their contribution to the marine and global carbon cycle (Aloisi et al., 2002; Judd et al., 2002; Judd, 2003).

Cold-water coral habitats occur in a wide range of geological settings and different ecosystems, a compilation is presented by Roberts et al. (2009). With respect to cold seep environments, the investigation of associated cold-water corals may provide important constraints on the impact of fluid emanation on the bottom water chemistry, supporting quantification and reconstruction attempts. Furthermore, a combination of contemporaneous cold-water coral and cold seep carbonate archives would be especially useful for the calibration of isotope proxies for carbonate precipitation conditions of cold seep environments in the past.

According to a hypothesized relationship between the occurrence of cold-water corals and hydrocarbon seepage (Hovland and Thomsen, 1997) and contradictory findings (Becker et al., 2009) our approach is focused on the geochronology of cold-water coral occurrence and cold seep activity. Additionally, the detection of age gaps between coral growth and formation of the underlying hard substrate could provide information about the time interval required for coral settlement and potentially related changes of hydrodynamic controls (Mienis et al., 2007; Roberts et al., 2006; White et al., 2005).

RV SONNE cruise SO191 to the Hikurangi Margin (Bialas et al., 2007) provided ideal samples of seafloor carbonate pavements and cold-water corals, which were recovered with a large video-guided grab (TVG). Cross-cuts through these large (up to $1.8 \times 1.2 \times 1$ m) blocks from three different sampling areas (Fig. 1A, Table 1) provide a geochronological, geochemical, mineralogical and structural view into carbonate precipitation processes at the seafloor and the development of the fluid 'plumbing' system through time.

The detailed investigation of cold seep carbonates from the tectonically highly active Hikurangi Margin fills a gap in the over-regional view on circum-Pacific cold seep areas of different geological settings like Hydrate Ridge (mature accretionary system), offshore Costa Rica (erosive subduction) and the South China Sea (passive continental margin).

On regional scale the investigation of fluid pathway structures and the timing of intensified fluid emanation contributes to the assessment of direct fluid flux measurements at active seep sites (Linke et al., this issue), when compared to the past. Furthermore, it supports interpretation and understanding of cold seep structures recovered on land on the North Island of New Zealand (Nymann et al., this issue).

2. Regional setting and sampling sites

The Hikurangi Margin at the east coast of New Zealand's North Island is characterized by the oblique subduction of the Pacific plate beneath the Australian plate (Fig. 1). The convergence rate varies from 45 mm yr^{-1} in the North Island region to 38 mm yr^{-1} in the northern South Island region forming a large accretionary prism with a series of accretionary ridges with active cold seeps offshore and fossil ones onshore (Barnes et al., this issue; Campbell et al., 2008; Lewis and Marshall, 1996).

Fossil cold seeps are described for northern Wairarapa (Lederset et al., 2003) and large tubular carbonate concretions (50–85% carbonate) with near-central conduits are interpreted as part of a subsurface plumbing network of a paleo cold seep system in coastal cliffs north of Cape Turnagin (Nymann et al., this issue). These findings demonstrate that fluid venting at the Hikurangi Margin is a long lasting phenomenon.

In this study we focus on the analyses of carbonate samples obtained from three study areas during SONNE cruise SO191 — Opouawe Bank, Uruti and Omakere Ridge (Fig. 1) in order to cover different settings along the Hikurangi Margin. All seep sites lie on separate crests of thrust-faulted ridges at mid-slope depths (Barnes et al., this issue). They are positioned near the seaward edge of the Cretaceous and Paleogene basement rocks, which constitute a relatively impermeable backstop that focuses fluid migration offshore today along low-angle thrust faults and the décollement (c.f. Lewis and Marshall, 1996; Barnes et al., this issue). Fault fracture networks are visible in seismic images beneath the seeps, and bottom simulating reflectors (BSR) are disturbed at these locations by upward fluid and gas migration to the seafloor seep sites (Barnes et al., this issue; Netzeband et al., this issue).

2.1. Opouawe Bank

The Opouawe Bank is one of the accretionary ridges culminating in about 900 m water depth and well separated from the continental slope by erosive canyons (c.f. Klaucke et al., this issue). High-resolution side-scan sonar data collected over Opouawe Bank indicated thirteen different cold seeps (Greinert et al., this issue), which Klaucke et al. (this issue) divide into two types: high acoustic

Fig. 1. Compilation of bathymetry, site distribution and seafloor observation during the deployment of TV-guided grabs, *RV SONNE* cruise SO191. A: Overview map showing the bathymetry of the Hikurangi Margin at the east coast of New Zealand's North Island. The squares mark the sampling areas of this study. Lake Taupo appears in light grey in the central part of the island. B: Typical seafloor observation of cold seep faunal community and blocks of less mature calcified sediments at Bear's Paw (Omakere Ridge). C: The white square marks the recovered sample at station # 165 (each picture width: approx. 2 m). D: Sampled cold-water coral reef structures (station # 227) on top of authigenic carbonates at the Moa site of Omakere Ridge (picture width approx. 2 m). Insertion shows enlargement of a recovered fragment (white square) of a living reef-forming colony. E: Flat, fractured and mature calcified pavement-like seafloor at the top of Uruti Ridge close to the LM-10 site (station # 316). The white square marks the recovered solid block (picture width approx. 2 m). F: Characteristic high relief seafloor with large separated blocks and chemoherm structures indicating pronounced exposure due to erosional conditions at the North Tower site of Opouawe Bank. The white square marks the sampled block at station # 138 (pict. width: approx. 4 m). G: Enlarged documentation of the upright in-situ position of the largest cold seep carbonate sample recovered since (station # 138, picture width approx. 2.5 m).