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New records of Oligocene diffuse hydrocarbon seeps, northern Cascadia margin

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ABSTRACT

Fossil methane seeps are preserved in late Eocene through Pliocene marine sedimentary units of the Cascadia margin of the northeastern Pacific. All Cascadia fossil seeps are situated in the uplifted accretionary wedge that overlies extensive Middle Eocene coal-bearing units and the Paleocene–Early Eocene Siletzia large igneous province. This study describes eight previously unrecorded Oligocene seeps, all of which are identified by small, scattered carbonates with or without accompanying characteristic seep macrofauna, from both inner and outer shelf depths. We interpret these deposits as reflecting spatially and temporally diffuse seepage of hydrocarbon-enriched fluids, sourced from various carbon sources within the actively deforming accretionary prism, and term them diffuse seeps. $\delta^{13}C$ and $\delta^{18}O$ values from foraminiferal carbonate from the studied stratigraphic units have broad variability. Authigenic carbonates occurring as nodules, blebs, burrow fill and fracture fill indicated microbial and thermogenic methane, and multiple fluid flow pathways from within the actively deforming accretionary wedge. It is apparent that the complex fluid-flow regime observed in modern seeps of the Cascadia margin is a continuation of one established in the late Eocene.

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1. Introduction

Methane seeps are widely known from tectonically active and passive margins worldwide. Modern seeps are recognized by distinctive faunal communities and by physical features such as gas bubbles and characteristic mineral deposits (e.g. Teichert et al., 2005). Methane seeps are thought to contribute significantly to the global methane inventory (e.g. Milkov et al., 2003; Etiope and Milkov, 2004). In the rock record, fossil methane seeps are known from numerous localities on active tectonic margins including New Zealand, Italy and California and the Cascadia margin of the western United States (Goedert and Squires, 1990; Campbell et al., 2002; Goedert et al., 2003; Barbieri and Panieri, 2004; Campbell et al., 2008; Panieri et al., 2009).

Fossil methane seeps are preserved in late Eocene through Pliocene marine sedimentary units of the Cascadia margin (Fig. 1), which extends from northern California to southwestern Vancouver Island, British Columbia (Campbell, 1992; Goedert and Squires, 1993; Peckmann et al., 2002; Goedert et al., 2003; Campbell et al., 2006; Martin et al., 2007). This study focuses on eight previously undescribed seeps (Fig. 2, Table 1), all of which are identified by small, scattered carbonates with or without accompanying characteristic seep macrofauna. Authigenic inorganic and biogenic (benthic foraminifera tests) samples were taken from the Oligocene Blakeley, Pysht, Makah, and Lincoln Creek formations of Washington State, and the Sooke Formation of southern Vancouver Island. This study also analyzed foraminiferal carbonates sampled from a previously described seep in the Lincoln Creek Formation (Peckmann et al., 2002, site SR4). Stable isotopes of the authigenic carbonates and associated foraminiferal carbonate carbon aid in the identification and characterization of these relatively subtle fossil seep deposits. These fossil seeps do not contain large carbonate bodies such as chemoherms, pipes or chimneys, nor do they have extensive assemblages of chemosynthetic organisms typical of previously described fossil seeps (e.g. Goedert and Squires, 1990; Campbell and Bottjer, 1993; Goedert et al., 2003; Barbieri and Panieri, 2004; Campbell et al., 2008; Panieri et al., 2009). The presence of extensive carbonate bodies and dense faunal assemblages suggests a relatively long fluid-flow history or a high rate of fluid expulsion (Johnson et al., 2006). The seeps investigated in this study, however, are typified by scattered occurrences of small carbonate bodies such as nodules and blebs, and occasional occurrences of chemosynthetic taxa such as solemyid bivalves. We therefore term these diffuse seeps, and infer that they were caused by ephemeral and/or weak fluid flow derived from various carbon sources within the actively deforming accretionary prism.

Cenozoic Cascadia subduction was initiated in the Late Eocene, marked by rise of the ancestral Cascade volcanic arc mountains parallel to the coastline. Voluminous siliciclastic sediments were shed from this growing mountain chain into the forearc, building a substantial accretionary prism with rapid deepening of the forearc (Snavely and Wells, 1996; Brandon et al., 1998; Wells et al., 1998; Stewart and Brandon, 2004; du Bray and John, 2011). Numerous Oligocene seep deposits have been reported from the northern Cascadia continental margin

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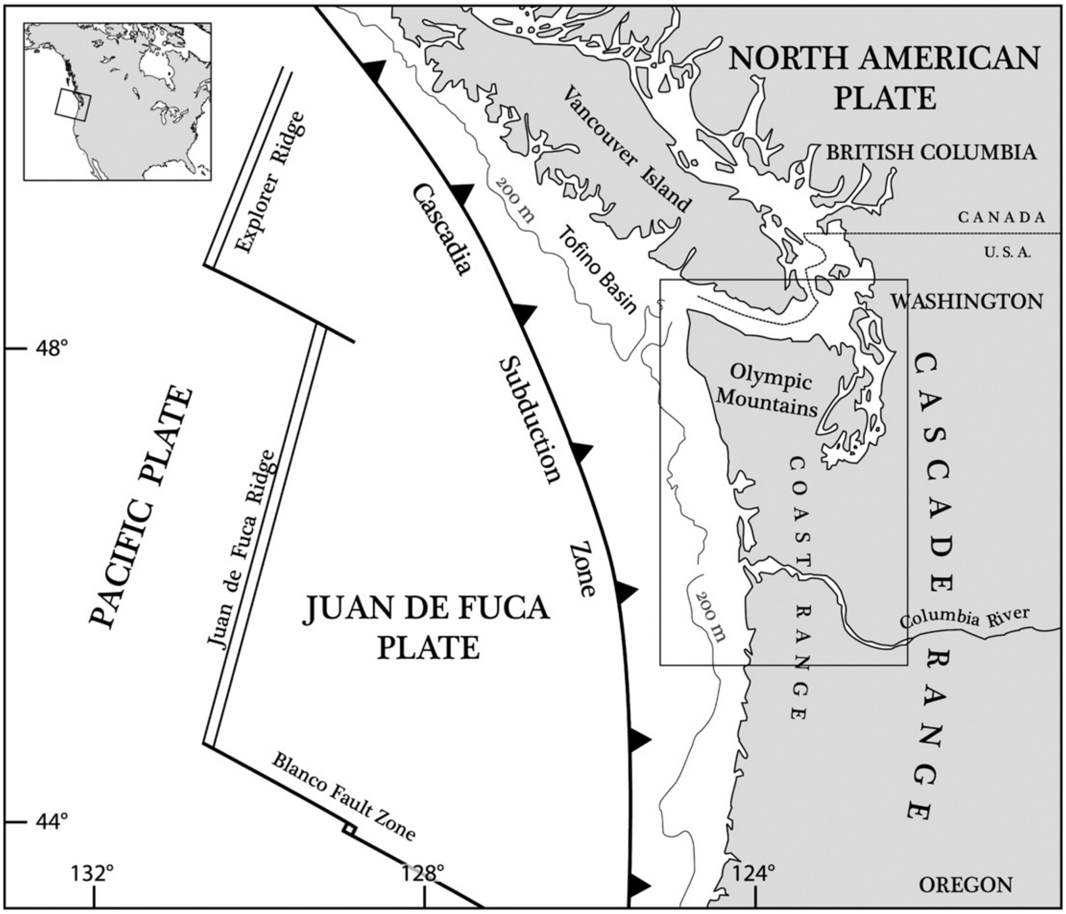

Fig. 1. Map of the Cascadia margin. Box denotes area of Fig. 2.

enclosed in thick, fine-grained, volcaniclastic marine sequences of uplifted, faulted and imbricated accretionary wedge strata (see references in Table 2). Beginning in the Middle Miocene, the geometry of the North American Plate in northern Cascadia forced the accretionary wedge above sea level during Juan de Fuca Plate subduction, forming the Olympic Mountains (Fig. 1; Wells et al., 1998; Stewart and Brandon, 2004). In the Late Miocene, a tectonic deformation and uplift event across the entire margin led to erosion of the shelf (McNeill et al., 2000). Pliocene age seeps occur in inner to middle shelf sedimentary strata from geographically isolated coastal cliff exposures in western Washington (Campbell, 1992, 2006). The rest of the accretionary wedge is still below sea level and undiscovered Pleistocene and modern oil and gas seeps are likely to be extensive in this offshore region.

2. Geotectonic setting and stratigraphy of Oligocene Cascadia seeps

2.1. Geology and tectonic setting

The doubly vergent Cascadia accretionary wedge was formed by subduction of various oceanic plates (Farallon, Resurrection, Pacific, Juan de Fuca) beneath the North American Plate since the Late Eocene (Fig. 1; Willett et al., 1993; Haeussler et al., 2003; Madsen et al., 2006). Offshore today, the Cascadia accretionary wedge extends westward from the continental margin to the nearly filled subduction trench, and has grown by frontal accretion and underplating, youngest to the southwest (Tabor and Cady, 1978; Brandon et al., 1998; Stewart and Brandon, 2004). The current deformation front is situated ~140 km west of the central Washington coastline and seismic imaging shows it to be ~3 km thick at the trench and up to 35 km thick beneath the Olympic Mountains (Clowes et al., 1987; Parsons et al., 1999). This subduction-related sedimentary package overlies geographically extensive Paleocene to Early Eocene volcanic basement rocks of the Coast Range Basalt Province, or Siletzia terrane. Since the Late Eocene, the Siletzia terrane – comprising the Metchosin Igneous Complex of Vancouver Island, the Crescent Formation in Washington, and the Siletz River Volcanics in Oregon – has served as the basement backstop to the accretionary prism sediments scraped off of the subducting oceanic plate (Wells et al., 1984; Snavely and Wells, 1996; Stewart and Brandon, 2004). The Siletzia terrane formed as an oceanic igneous plateau, ~35 km thick in the south and 19 km thick where it is exposed on the Olympic Peninsula (Brandon et al., 1998). Siletzia rocks consist of voluminous, high-Ti, tholeiitic and alkali basalts that erupted off, but close to, the continental margin from ~60 Ma. Accretion onto the margin of the North American Plate occurred during the last phase of eruption (Duncan, 1982; Snavely and Wells, 1996). Three hypotheses have been proposed for the formation of Siletzia: 1) the plume head of the Yellowstone hotspot, positioned off the coast during the early Paleogene (Duncan, 1982; Babcock et al., 1992; Pyle and Mather, 2009); 2) a rift margin that resulted from highly oblique subduction of the Farallon Plate, creating a narrow, elongate pull-apart basin (Wells et al., 1984; Clowes et al., 1987; Babcock et al., 1992); or 3) a mid-ocean ridge spreading center between the now subducted Farallon Plate and the hypothesized Resurrection Plate, positioned close to the continental margin during the Paleocene and Early Eocene (Haeussler et al., 2003; Madsen et al., 2006).

During the Early and Middle Eocene, terrestrially derived sediments onlapped the basaltic basement, with the oldest units (Umpqua