Corals from deep-water methane-seep deposits in Paleogene strata of Western Oregon and Washington, U.S.A.

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Abstract. In general, fossils of corals are rare within Eocene and Oligocene marine strata that accumulated in a deep-water, convergent-margin setting and are now exposed in western Oregon and Washington, northwestern USA. At some localities, however, specimens of a few coral taxa are relatively abundant and associated with authigenic limestone deposits. Recently, these highly-localized limestone deposits were recognized as having precipitated due to the microbial oxidation of methane at seeps, areas where hydrocarbon-rich fluids were vented to the sea floor because of the tectonic compression and faulting of underlying sediments. As at modern methane-seeps, the ancient seeps supported dense invertebrate communities, in most cases dominated by tube-dwelling worms and bivalve mollusks, but they can also include gastropods, polyplacophorans, sponges, and corals. A few methane-seep assemblages in Eocene and Oligocene rocks of the Lincoln Creek Formation include the corals *Caryophyllia wynoocheensis* Durham, and an undescribed *Flabellum* (*Ulocyathus*) species. A new species of *Deltocyathus* appears to be restricted to a single methane-seep site. The corals *Stephanocyathus holcombensis* Durham, and *Flabellum hertleini* Durham have been reported from what may be methane-seeps sites in the Lincoln Creek Formation near Holcomb, Washington, and associated with an unusual crinoid-rich bioherm in the Keasey Formation near Mist, Oregon. Other corals, *Flabellum* (*Ulocyathus*) n. sp., *Archohelia*? sp., *Caryophyllia wynoocheensis*, and *Dendrophyllia hannibali* Nomland, are reported from a Lincoln Creek Formation locality that includes methane-seep related assemblages near Knappton, Washington. Although widespread in the deep sea today, none of the genera found in the ancient seeps in Washington and Oregon have yet been reported from modern seeps, and corals have rarely been reported from pre-Tertiary methane-seep deposits. It is unlikely that any of these corals, like the bivalves and tubeworms found at methane-seeps, hosted and derived nutrients from

Freiwald A, Roberts JM (eds), 2005, *Cold-water Corals and Ecosystems.* Springer-Verlag Berlin Heidelberg, pp 27-40

endosymbiotic chemotrophic bacteria that were capable of metabolizing some of the reduced compounds in the seeping fluids. More likely, the corals probably were attracted to the greater amount of food at seeps relative to the surrounding deep sea, or to the attachment sites provided by hardgrounds of methane-derived carbonate deposits on the muddy seafloor.

Keywords. Corals, methane, Paleogene, Oregon, Washington

Introduction

Outcrops of Eocene and Oligocene deep-water marine strata are widespread in western Oregon and Washington, in the northwestern USA. Fossil invertebrate assemblages from these rocks have been studied for more than a century (e.g., Conrad 1848; Weaver 1943; Durham 1944; Hickman 1969; Moore 1984). Fossils of corals in these deposits are, however, relatively rare. Other than incidental inclusion in reports on molluscan assemblages, Tertiary corals from Washington and Oregon have been the sole subject of only a few reports (Durham 1942; Blake 1968). At a few localities, deep-water corals increase in abundance and this appears to reflect some highly-localized paleoecological effect such as, for example, methane seepage.

Modern methane-seeps support dense communities of invertebrates that rely on the oxidation of reduced seepage compounds (hydrogen sulfide and methane) by endosymbiotic bacteria hosted in their tissues (Sibuet and Olu 1998, and references therein). Apart from these chemosymbiotic communities, authigenic carbonates with low $\delta^{13}C$ values are another typical feature of methane-seeps. Here, carbonate formation results from the anaerobic oxidation of methane (AOM) by a microbial consortium of methanotrophic archaea and sulfate-reducing bacteria; this consortium was isolated by Boetius et al. (2000) for the first time. Carbonate precipitation at methane-seeps is consequently confined to anoxic environments (Peckmann et al. 2001). Seep carbonates are essentially the product of microbial activity as revealed by their low $\delta^{13}C$ values documenting the incorporation of methane-derived carbon, isotopically-depleted biomarkers of the AOM-performing consortium, and microbial carbonate fabrics (Peckmann et al. 2002).

The fossils from Washington were found in bathyal sediments that accumulated in a convergent-margin, forearc setting (Armentrout 1987). These strata also enclose localized, anomalous, authigenic limestone deposits (Goedert and Squires 1990; Squires and Goedert 1991; Campbell 1992; Campbell and Bottjer 1993; Peckmann et al. 2002). These limestones were recently recognized as being the product of the ancient microbial oxidation of methane in areas where hydrocarbon-rich fluids were vented to the sea floor. This seepage of pore waters occurred due to the compression and faulting of underlying sediments as the Juan de Fuca plate was subducting beneath the North American plate, a continuing process that began in Late Eocene time (Vance et al. 1987; Kulm et al. 1986; Ritger et al. 1987). At some places on the seafloor where seepage of hydrocarbons occurs today, carbonate chimneys, crusts, and other structures can be found (Schroeder et al. 1987; Kulm and Suess 1990). As at modern methane-seeps, many ancient seeps supported dense invertebrate

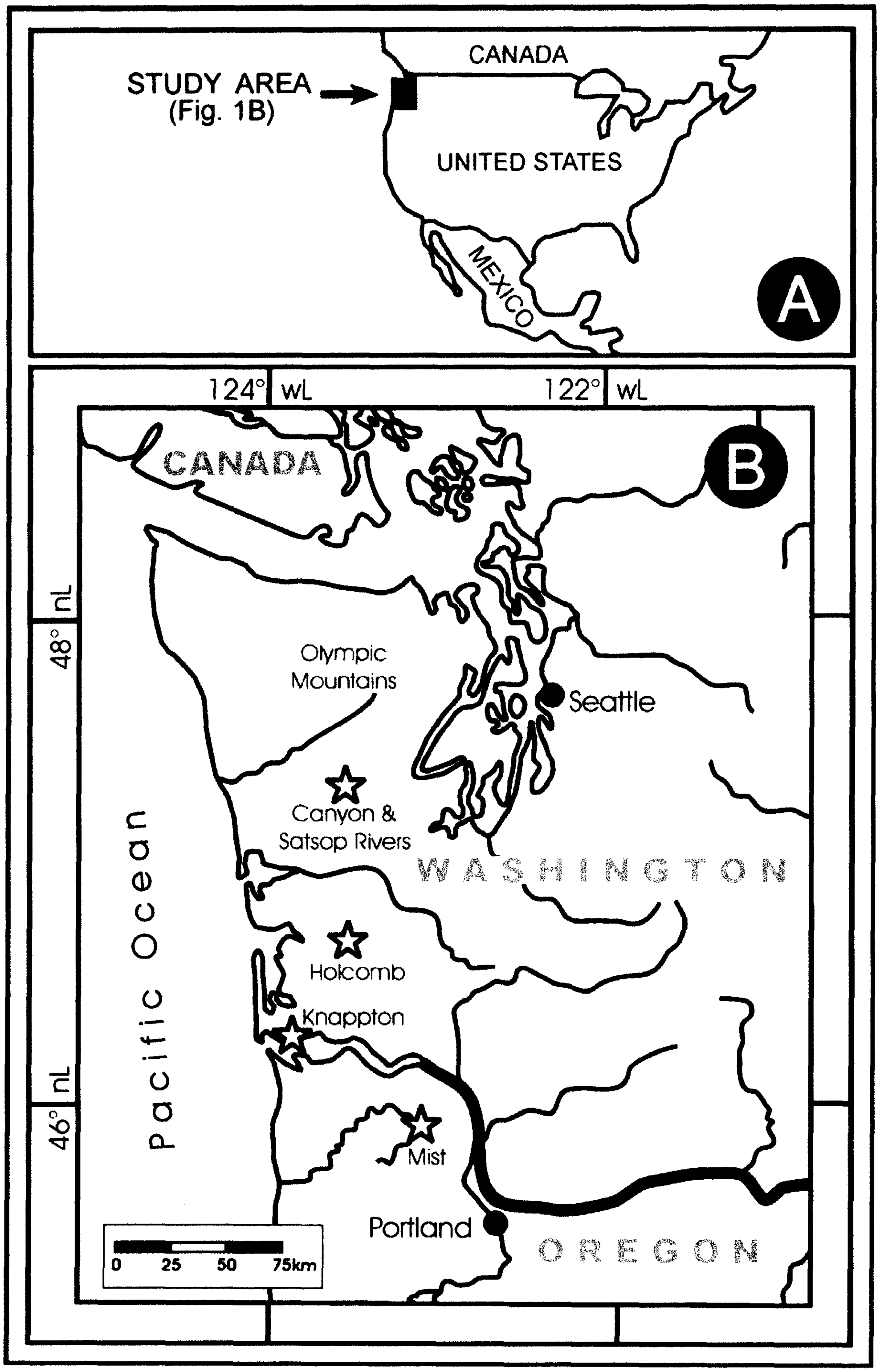

Fig. 1 A Index map of USA showing the study area. **B** Map of western Washington and Oregon showing proven and suspected methane-seep coral localities

communities (e.g., Gaillard et al. 1985; Taviani 1994; Majima 1999; Peckmann et al. 1999; Kelly et al. 2000; Campbell et al. 2002). In most cases, Tertiary seep assemblages were dominated by tube-dwelling worms and bivalve mollusks, on the floor of the relatively nutrient-poor and otherwise nearly barren deep sea. Worm tubes, bivalves, gastropods, polyplacophorans, sponges, and in a few cases, corals (Peckmann et al. 2002) have been found in the Eocene and Oligocene seep deposits in Washington State. Methane-seep deposits have been recognized in several formations in western Washington, ranging in age from middle Eocene to Pliocene (Campbell and Bottjer 1993; Orange and Campbell 1997) but corals have only been found in seep deposits identified within various geographically widespread outcrops (Fig. 1) of the Lincoln Creek Formation.

The primary aim of this paper is to record those corals that have been found in association with both proven and suspected methane-seep deposits in Washington. Institutional abbreviations used for specimen and locality numbers are: UWBM, The Burke Museum of Natural History and Culture, University of Washington, Seattle, Washington 98195; and LACMIP, Natural History Museum of Los Angeles County, Invertebrate Paleontology, 900 Exposition Boulevard, Los Angeles, California 90007.

Lincoln Creek Formation

Southern flank of the Olympic Mountains

South of the Olympic Mountains, in the Satsop and Canyon River valleys, the Lincoln Creek Formation is approximately 3000 m thick (Rau 1966) and provides a nearly continuous depositional record from Late Eocene to latest Oligocene time (Prothero and Armentrout 1985). Deposition occurred at depths of between 400 and 800 m (Rau 1966), but in places, possibly less than 210 m (Peckmann et al. 2002). Methane-seep deposits are relatively common throughout the formation in this area (Campbell and Bottjer 1993; Squires 1995; Peckmann et al. 2002). The corals that have been identified in these methane-seep deposits include at one site a new species of *Deltocyathus* (Figs. 2a, 3a-d; Appendix 1) that has not been found anywhere else, *Caryophyllia wynoocheensis* Durham, 1942 (Figs. 2b-d), and a new species of *Flabellum* (*Ulocyathus*) (Fig. 2e). The *Flabellum* is referred to the subgenus *Ulocyathus* on the basis of the serrate calicular edge, but more complete specimens are needed to formally describe the species. *Caryophyllia wynoocheensis* is also found away from seep deposits (Durham 1942; Armentrout 1973). This is only the second record for *Deltocyathus* for the eastern North Pacific Ocean (Peckmann et al. 2002), and the first fossil record for the subgenus *Ulocyathus* from western North America.

Willapa River

Along the banks of the Willapa River near Holcomb, Washington, in a Late Eocene or Early Oligocene exposure of the Lincoln Creek Formation, is a locality that is suspected to be an ancient methane-seep site (Nesbitt et al. 1994: 1D-8).

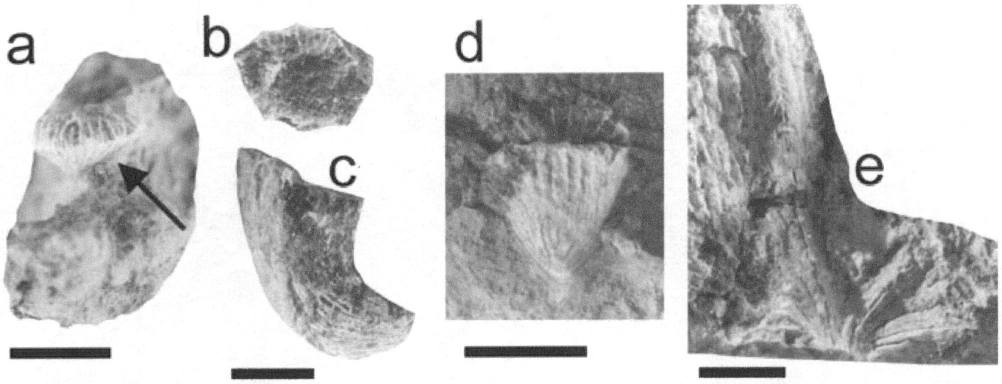

Fig. 2 Fossil methane-seep-associated corals from the Satsop and Canyon River localities. **a** *Deltocyathus insperatus* new species, referred specimen UWBM 97520, lateral view, scale is 5 mm. **b** *Caryophyllia wynoocheensis* Durham, 1942, UWBM 97524, UWBM loc. B6782, calicular view, scale for b and c is 5 mm. **c** Same specimen as **b**, lateral view. **d** *Caryophyllia wynoocheensis*, UWBM 97525, UWBM loc. B6783, lateral view, scale is 10 mm. **e** *Flabellum* (*Ulocyathus*) sp., UWBM 97526, UWBM loc. B6783, lateral view, scale is 10 mm

Very large solemyid and abundant thyasirid bivalves have been reported from this locality (Weaver 1943; Armentrout 1973) along with corals (Durham 1942). Solemyid and thyasirid bivalves are common constituents of modern and ancient methane-seep assemblages (e.g., Campbell and Bottjer 1993; Sibuet and Olu 1998). Two corals, *Stephanocyathus holcombensis* Durham, 1942, and *Flabellum hertleini* Durham, 1942, are fairly abundant at the Holcomb site. The molluscan fossils from this locality were regarded as being a "deep-water" assemblage by Hickman (1984), but estimates of water depth vary from approximately 20 to 100 m (Armentrout 1973), to more than 200 m (Hickman 1980).

Knappton

Corals have been reported (Moore 1984) from the Lincoln Creek Formation near Knappton, Washington, at localities that include methane-seep related assemblages (Goedert and Squires 1993). Fossiliferous concretions from the Lincoln Creek

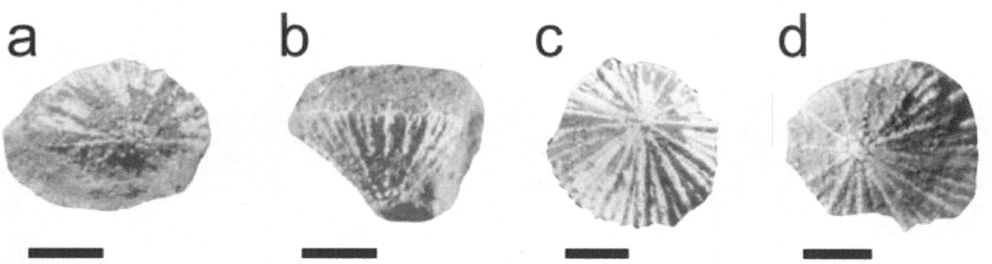

Fig. 3 *Deltocyathus insperatus* new species (see Appendix 1 for description). All from UWBM loc. B6781; all scales are 2 mm. **a** *Deltocyathus insperatus* new species, paratype UWBM 97521, basal view. **b** Same specimen as **a**, lateral view. **c** *Deltocyathus insperatus* new species, paratype UWBM 97522, basal view. **d** *Deltocyathus insperatus* new species, paratype UWBM 97523, basal view

Formation near Knappton are mostly found in modern landslide blocks (Moore 1984), but some methane-seep limestones have recently been found *in situ* (Goedert and Benham 2003). Some of the Knappton limestones are allochthonous ("Type 3" deposits of Conti and Fontana 1998), having been transported from the original seep site and redeposited by debris flows or turbidity currents. Paleobathymetry of the Lincoln Creek Formation at Knappton was estimated to have been 100 to 350 m, based on mollusks, or as deep as 1000 m, based on foraminiferans (Moore 1984). Moore (1984) reported the corals *Flabellum* sp. and *Dendrophyllia hannibali* Nomland, 1916, from the Knappton locality.

The *Flabellum* sp. reported by Moore (1984) is actually a new species, referred to as *Flabellum* (*Ulocyathus*) n. sp. herein. Specimens of *Flabellum* (*Ulocyathus*) n. sp. (Figs. 4a-d) from Knappton are moderately abundant, and are in all cases found in carbonate nodules. They are complete and unabraded, and the few coral-bearing nodules found *in situ* do not appear to have been reworked. They are more expanded than the specimens from the Lincoln Creek Formation south of the Olympic Mountains, but more specimens are needed for a formal description.

One block of carbonate containing abundant echinoid spines and a few "mud pectens" also contained a single specimen of *Caryophyllia wynoocheensis* (Fig. 4e). We also collected a nodule containing numerous branches of *Archohelia*? sp. that had overgrown, or intergrown with, a hexactinellid sponge (Figs. 4f-h). Hexactinellid sponges have been reported from several methane-seep sites in Washington (Rigby and Jenkins 1983; Rigby and Goedert 1996; Peckmann et al. 2002), and in some cases they appear to have been the dominant faunal component. Some of the seep limestone blocks found at Knappton also contain hexactinellid sponges.

The corals from Knappton are not clearly indicative of the past presence of a methane-seep, but their abundance, coupled with the common occurrence of seep limestones in the same strata seem more than coincidental.

Mist, Oregon

The corals *Stephanocyathus holcombensis* and *Flabellum hertleini* have been found associated with an unusual crinoid-rich bioherm in the Early Oligocene Keasey Formation near Mist, Oregon, that is suspected to be yet another seep site (Burns and Mooi 2003). Solemyid bivalves, pogonophoran tubes, asteroids, and ophiuroids were also found in the localized Mist assemblage, while the surrounding strata are nearly barren of megafossils. Based on data from several sources, water depths of approximately 300 to 450 m are likely for this site (Burns and Mooi 2003). Further investigations are underway on this site by C. Burns (Seattle) and K.A. Campbell (Auckland).

Discussion and conclusions

Although corals have been reported from several present-day methane-seeps worldwide (e.g., Sibuet and Olu 1998), none of the genera found in the ancient seeps in Washington have yet been reported from modern seeps. Ancient marine

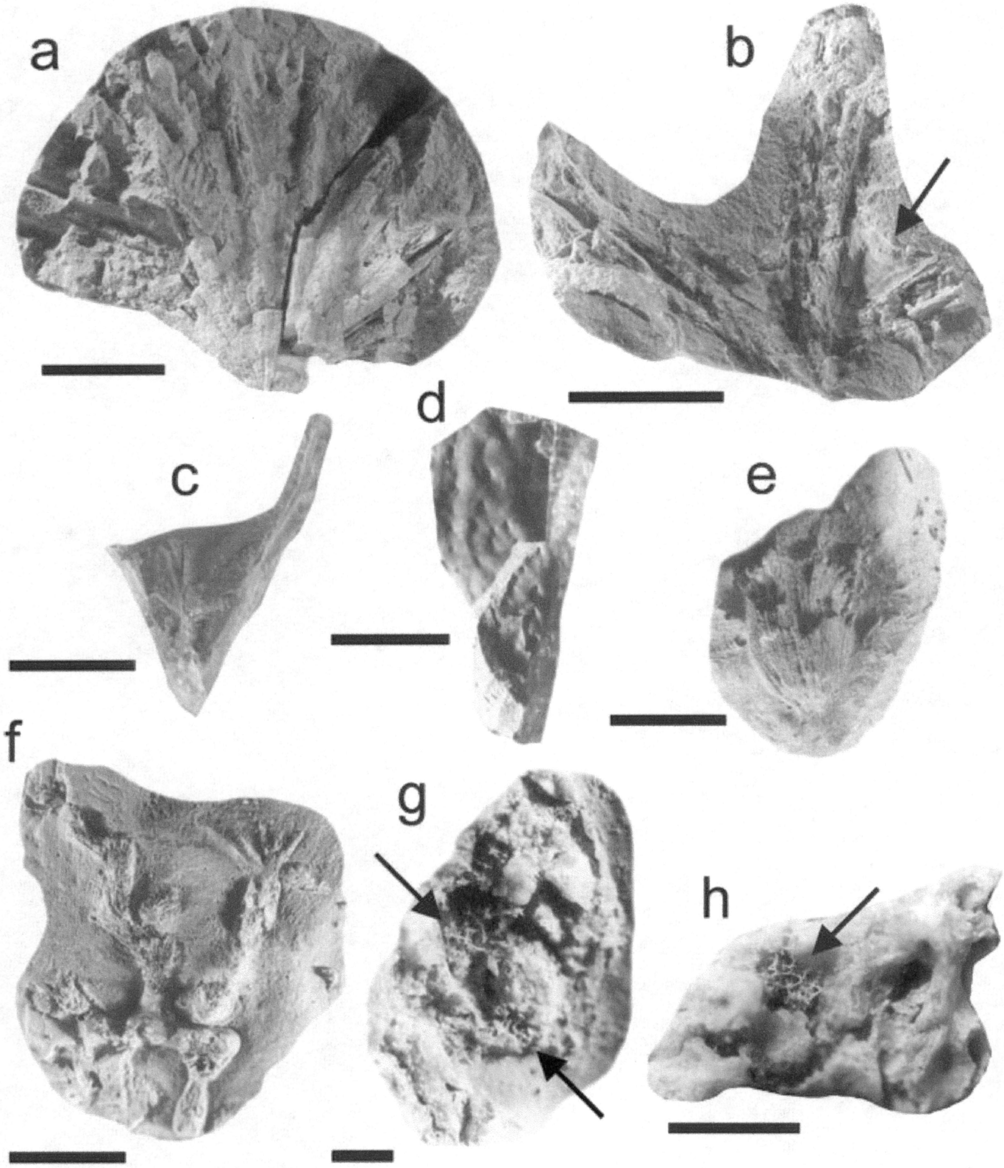

Fig. 4 Corals from the Lincoln Creek Formation near Knappton, Washington. **a** *Flabellum* (*Ulocyathus*) n. sp., UWBM 97529, LACMIP loc. 5842, lateral view, scale is 10 mm. **b** *Flabellum* (*Ulocyathus*) n. sp., UWBM 97530, LACMIP loc. 5842, fragment in lateral view showing growth lines (arrow), scale is 10 mm. **c** Same specimen as **a,** side view of specimen showing calicular expansion, scale is 10 mm. **d** Same specimen as **a**, view of septal faces showing pits, scale is 5 mm. **e** *Caryophyllia wynoocheensis*, UWBM 97527, LACMIP loc. 5843, lateral view, scale is 10 mm. **f** *Archohelia*? sp., UWBM 97528, LACMIP loc. 5843, scale is 10 mm. **g** Same specimen as **f**, view of basal portion of colony intergrown with the basal part of a hexactinellid sponge (arrow), scale is 2 mm. **h** Same specimen as **f** and **g**, note sponge skeletal fragment (arrow) in coral, scale is 5 mm

vent and seep paleocommunities range in age from Silurian to Pliocene and have been reported from many parts of the world (Campbell and Bottjer 1995; Little et al. 1998; Campbell et al. 2002). There are, however, very few reports of corals from methane-seep assemblages older than Late Eocene (Schwartz et al. 2003; Shapiro, in press). Reasons for this are not at all clear, but the near absence of corals from pre-Eocene seeps may be a sampling bias related to the greater abundance of geochronologically younger seep deposits.

The deep-water corals from the Lincoln Creek Formation in Washington may have been attracted to seeps because of the firm substrates offered by methane-derived carbonate deposits, or by the greater production and relative abundance of food near seeps. Some small corals like *Deltocyathus* may be automobile (Gill and Coates 1977; Plusquellec et al. 1999). Automobility would be a useful attribute for a solitary coral living near methane-seeps enabling it to cope with bioturbation by bivalves (e.g., vesicomyids), to avoid toxicity due to concentrations of various seepage compounds (e.g., hydrogen sulfide), and to continuously reposition itself in order to optimize feeding opportunities.

Hovland and Thomsen (1997) and Hovland et al. (1998) originally proposed a link between the occurrence of the reef-forming deep-water coral *Lophelia pertusa* and hydrocarbon seepage. This idea is still put forward by its advocates (Hovland and Risk 2003), but there is no unambiguous evidence to corroborate this scenario. Corals live on seepage-related mounds in the northeastern Atlantic Ocean off Ireland, but are only part of a community of suspension-feeders that apparently find the elevation of the mound to be beneficial (Masson et al. 2003). Likewise, other recent studies on coral-topped carbonate mounds in the Rockall Trough off Ireland found no evidence for a link between hydrocarbon seepage and coral growth (Kenyon et al. 2003; van Weering et al. 2003). The fact that *Lophelia* has been found to be largely dependant on zooplankton and, thus, on the transfer of pelagic particles and food from the productive surface waters (Freiwald et al. 2002) is also not in favor of the postulated link to hydrocarbon seepage.

In some cases, the fossil, seep-associated corals appear to have been only attached to the surface of the carbonate after both seepage and carbonate formation had stopped. For example, the specimen of *Caryophyllia wynoocheensis* in Figures 2b-c was found on the top of a small carbonate deposit, with its base at the contact between the carbonate and the enclosing siltstone. In other cases, however, some corals (Figs. 2a, 2e, 3a-d) appear to have been part of the seep-associated invertebrate assemblage because they are found only in direct association with methane-seep carbonate and not elsewhere in the surrounding strata. For example, the new species of *Deltocyathus* from the Satsop River seep (UWBM loc. 6781) is found throughout the small limestone deposit and in direct association with vesicomyid, nuculanid, solemyid, and thyasirid bivalves. Therefore, the *Deltocyathus* were living at the seep during periods of active methane seepage. It is unlikely that the *Deltocyathus* were only taking advantage of the hard seep carbonate as a substrate, because they have not been found anywhere else (e.g., on whale bones, mollusk shells, other carbonates). The seep-associated invertebrate assemblage from UWBM loc. B6781 is one of the most diverse so far reported and includes some gastropod taxa not reported from any other seep, modern or ancient (Peckmann et al. 2002). Some of the gastropods (and most likely the new species of *Deltocyathus*) were dependent on some food source that was either restricted to or enhanced in some way by this particular seep.

Schwartz et al. (2003) reported specimens of an unidentified species of *Flabellum* associated with ancient methane-seep sites in the Maastrichtian-Danian Moreno Formation in California. It is suspected that *Flabellum* was attracted to the vicinity of the seep sites by the greater amount of food production by the seep paleocommunity (Schwartz et al. 2003).

Some coral species such as *Caryophyllia wynoocheensis* were apparently opportunists better able to take advantage of a variety of bottom conditions because it is also found at localities away from seeps. Living species of *Caryophyllia* commonly have wide geographic distributions (e.g., Cairns 1994).

It cannot be excluded that some of these corals, like the bivalves and tubeworms found at methane-seeps, had the ability to host and derive nutrients from endosymbiotic chemotrophic bacteria. This is, however, unlikely because this trophic strategy has not yet been demonstrated for living corals.

Acknowledgments

We thank A. Peckmann (Bremen) for the preparation of Figure 1. Simpson Timber Company provided access to their land. The following people participated in fieldwork resulting in this paper: G.H. Goedert, S. Klautsch, K.L. Kaler, F. Gill. We are grateful for the thorough reviews by M. Krautter (Hannover) and M. Taviani (Bologna) who greatly improved the manuscript. Special thanks to A. Freiwald (Erlangen) for editorial work. Financial support was provided by the 'Deutsche Forschungsgemeinschaft' through the DFG-Research Center for Ocean Margins, Bremen (contribution no. RCOM0115).

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Appendix 1

SYSTEMATIC PALEONTOLOGY

Order Scleractinia

Superfamily Caryophyllioidea Dana, 1846

Family Caryophylliidae Dana, 1846

Genus *Deltocyathus* Milne Edwards and Haime, 1848

Type species.—*Turbinolia italica* Michelotti, 1838, by monotypy.

Deltocyathus insperatus n. sp.

Figs. 2a, 3a-d

2002 *Deltocyathus* n. sp. – Peckmann, Goedert, Thiel, Michaelis, Reitner, p. 858, Fig. 3G

Description.- A small *Deltocyathus* with septa arranged in four cycles, appearing to have 48 septa in all specimens complete enough to count. Costae of unworn specimens have an uneven, smooth to sharply serrate appearance. Base of unworn specimens with a blunt central granule. Septa exsert, with S_1 being the most highly exsert, S_2 less so, and $S_{3\text{-}4}$ least exsert. Lateral septal faces with irregular arrangement of low, pointed to blunt spines.

Material.- Holotype, LACMIP 12981 (Peckmann et al. 2002: Fig. 3G); paratypes UWBM 97521-97523; referred specimen UWBM 97520.

Occurrence.- Found in only one methane-seep deposit on the Middle Fork of the Satsop River, Mason County, Washington, LACMIP loc. 17426 (= UWBM loc. B6781), Lincoln Creek Formation, Late Oligocene.

Etymology.- From Latin, *insperatus*, meaning surprising or unexpected, in reference to the occurrence in a methane-seep deposit.

Remarks.- *Deltocyathus insperatus* new species is similar to *D. conicus* and *D. italicus* in conical form, but the costae are less spinose. The septal faces of *D. insperatus* are also less spinose than those of *D. conicus*. *Deltocyathus insperatus* is a very small species, with the largest specimens all being less than 6 mm in diameter, and only 2.5 to 3.3 mm in height. There is no other fossil coral from western North America that can be confused with the new species. The only other West Coast species is *D. whitei* Durham, 1943, from the Paleocene age Lodo Formation in California, and it is much larger, with a flattened, discoid corallum. There is apparently no living species of *Deltocyathus* found in the eastern North Pacific Ocean (Cairns 1994).

Appendix 2

Locality descriptions

UWBM B6781: (= LACMIP loc. 17426) Lincoln Creek Formation, Late Oligocene
Map: Dry Bed Lakes, WA USGS Quad., 7.5' Ser., Topo., Provisional Edition 1990. MAP PUB ID 2509
Methane-seep carbonate deposit at water level, east bank of the Middle Fork of the Satsop River, approximately 80 m south and 240 m east of the northwest corner of Sec. 32, T. 21 N., R. 6 W., Mason County, Washington. (= SR4 of Peckmann et al. 2002).

UWBM B6782: Lincoln Creek Formation, Early Oligocene
Map: Dry Bed Lakes, WA USGS Quad., 7.5' Ser., Topo., Provisional Edition 1990.
Very small methane-seep carbonate, less than 50 cm in diameter (as exposed in 2002), south bank of the Middle Fork of the Satsop River, approximately 800 m south and 310 m east of the northwest corner of Sec. 20, T. 21 N., R. 6 W., Mason County, Washington.
(= SR1 of Peckmann et al. 2002).

UWBM B6783: Lincoln Creek Formation, Oligocene? (float)
Map: Grisdale, WA USGS Quad., 7.5' Ser., Topo., Provisional Edition 1990.
Methane-seep carbonate block found as float on a gravel bar in the Canyon River, SW1/4 SW1/4 NW1/4 of Sec. 36, T. 20 N., R. 7 W., Grays Harbor County, Washington.
Collected by J.L. Goedert and K.L. Kaler, 13 August 1994.

UWBM B6784: Lincoln Creek Formation, Late Eocene - Early Oligocene
Map: Dry Bed Lakes, WA USGS Quad., 7.5' Ser., Topo., Provisional Edition 1990.
Solitary coral found in carbonate deposit (methane-seep?), north side of the Middle Fork of the Satsop River, at upstream end of bend in river, approximately 460 m south and 820 m west of the northeast corner of Sec. 20, T. 21 N., R. 6 W., Mason County, Washington.
Collected by J.L. Goedert and F. Gill, 12 July 2003.

LACMIP 5842: Lincoln Creek Formation, Late Oligocene
Map: Knappton, WA USGS Quad., 7.5' Ser., Topo., 1973 Edition.
Fossils found as float on beach northeast of the townsite of Knappton, north shore of the Columbia River, N½ N½ Sec. 9, T. 9 N., R. 9 W., Pacific County, Washington.

LACMIP 5843: Lincoln Creek Formation, Late Oligocene
Map: Knappton, WA USGS Quad., 7.5' Ser., Topo., 1973 Edition.
Fossils found as float on beach northeast of the townsite of Knappton, north shore of the Columbia River, approximately 305 m south and 430 m east of the northwest corner of Sec. 9, T. 9 N., R. 9 W., Pacific County, Washington.