Chapter 14
An Eldorado for Paleontologists: The Cenozoic Seeps of Western Washington State, USA

Steffen Kiel

Contents

14.1 Introduction

Most seep communities occur in deep water and it requires certain geologic processes – particularly their preservation within carbonates and their uplift above sea-level – before paleontologists can study them. Just like their modern analogs fossil seeps are highly localized and finding them requires walking through endless meters of strata that are usually barren of megafossils. The outcrop situation in western Washington is far from being ideal because most of the area is covered in thick forest. Many seep deposits are exposed along, sometimes even in, river beds (Plate 31) and can be sampled only at certain times of the year when water levels are low. Sites at coastal outcrops may only be reached by kayak or canoe, during low tide or only early in the year before they are covered by algal growth.

S. Kiel (✉)
Institut für Geowissenschaften, Christian-Albrechts-Universität,
Ludewig-Meyn-Str. 10, 24118 Kiel, Germany
e-mail: steffen.kiel@gmx.de

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Nevertheless, extensive searching over the past 20 years produced seep fossils that are unrivaled world-wide in their diversity and the quality of their preservation (Plate 32), and they are now probably the best-studied fossil seep faunas on Earth. A particular appeal is the fact that the seep-bearing sediment also revealed diverse whale-fall (Squires et al. 1991; Goedert et al. 1995) and wood-fall communities (Lindberg and Hedegaard 1996; Kiel and Goedert 2006b) so that evolutionary interactions between these ecosystems can be traced through nearly 45 million years of time (e.g., Kiel and Goedert 2006a). Furthermore, the seep carbonates preserve a wide range of molecular fossils (biomarkers) that reveal past fluid compositions, and the biochemical processes and microbial consortia involved in the precipitation of the carbonates, even on very small spatial scales (Peckmann et al. 2002, 2003; Goedert et al. 2003; Hoffmann 2006).

The history of their discovery began in 1979 when Jim and Gail Goedert made fossil collections from a limestone deposit in the Bear River area in Pacific County, Washington, and sent the specimens to the Los Angeles County Museum (LACM). Nothing was done until someone at LACM mentioned the large bivalves to Richard L. Squires, thinking that he might be interested in them because of his work on some vesicomyids from Dead Man's Island in California. This was about 1990, and Richard was the first to recognize that these might represent a fossil cold-seep fauna. Using a report on the limestone resources of western Washington (Danner 1966) Jim Goedert checked limestones found in similar depositional settings in the Lincoln Creek Formation (the Menlo deposit) and rocks now called the Humptulips Formation. Not surprisingly, the recovered fossils were similar to the Bear River limestone fauna. The resulting publication (Goedert and Squires 1990) was the starting shot to extensive and continuing research on fossil deep-water ecosystems in this area.

This chapter aims to give an overview of the fossil seep deposits in western Washington, their fauna, paleoecology, and mode of occurrence, to outline how these sites are recognized, and why they are exposed on land.

14.2 Fossil Seeps on Land: A Brief Tectonic History of Western Washington State

Most fossil seeps in western Washington are found within a tectonic unit called the Coast Range terrane (Brandon and Calderwood 1990; Stewart and Brandon 2004; Fig. 14.1). This unit consists of early Eocene basalts at the base with a thick cover of middle Eocene to early Miocene, seep-bearing marine sediments on top. There are different opinions in the literature as to where this terrane formed (either in situ, or as seamounts on the oceanic Farallon plate just to the southwest of their present-day position), and when it was accreted to the North American plate (50 versus 38 million years; see Snavely and MacLeod 1974; Babcock et al. 1992; Brandon and Vance 1992). What is important here is that the seep-bearing sediments of the Coast Range terrane were deposited before and after the subduction of the Juan de Fuca

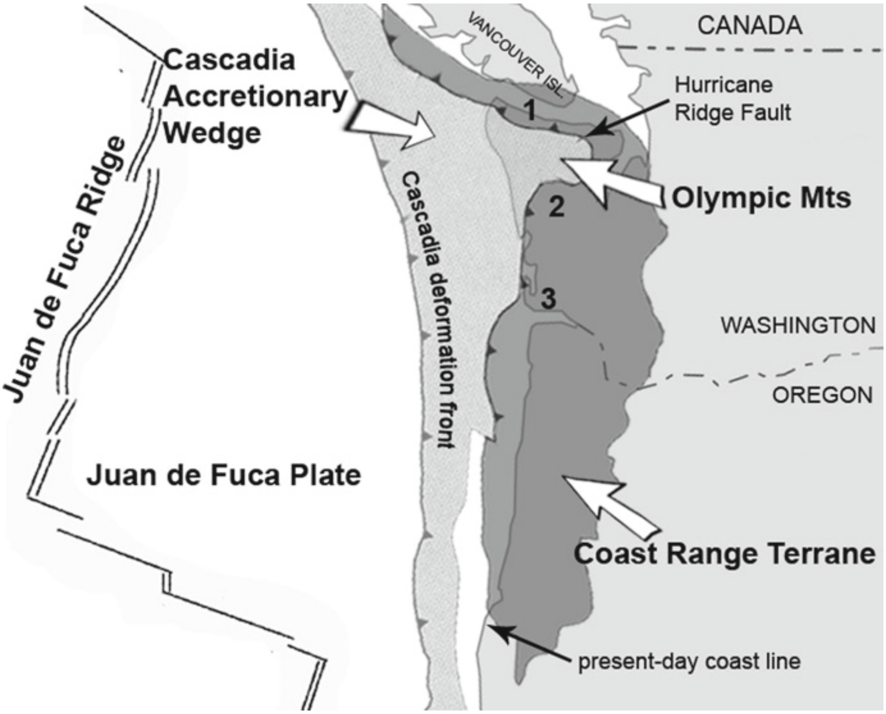

Fig. 14.1 Sketch of the tectonic setting of the Pacific Northwest. The major areas with fossil seeps are the Makah and Pysht formations along the north coast of the Olympic Peninsula (1), the Humptulips Formation and northern part of the Lincoln Creek Formation just south of the Olympic Mountains (2), and the Astoria and Lincoln Creek formations along the shore of the Columbia River (3) (Redrawn from Stewart and Brandon 2004)

plate beneath the North American plate began around 35 million years ago. This implies that the oldest seeps in western Washington (those of the Humptulips Fm) were deposited on a passive margin, whereas all younger seeps formed in an active, subduction-related setting.

Exhumation of the Coast Range terrane began in the middle Miocene about 15 million years ago, when the formerly straight, NNW trending Cascadia subduction zone acquired its modern, arched shape. While most subduction zones are concave toward the arc (the Aleutian and Java trenches are fine examples), the Cascadia subduction zone is concave seaward. The hinge point of this curved margin is located in the Olympic Mountains area. As a result, the subducting slab of the Juan de Fuca plate is forced to arch upward as it is subducted, which causes the uplift of the Olympic Mountains (Brandon and Calderwood 1990). Most of the Olympic Mountains belong to a tectonic unit called the Olympic Structural Complex, which is part of the Cascadia accretionary wedge. The Olympic Structural Complex is underplating the Coast Range terrane, along a major fault called the Hurricane Ridge fault (Fig. 14.2). Thus while the Olympic

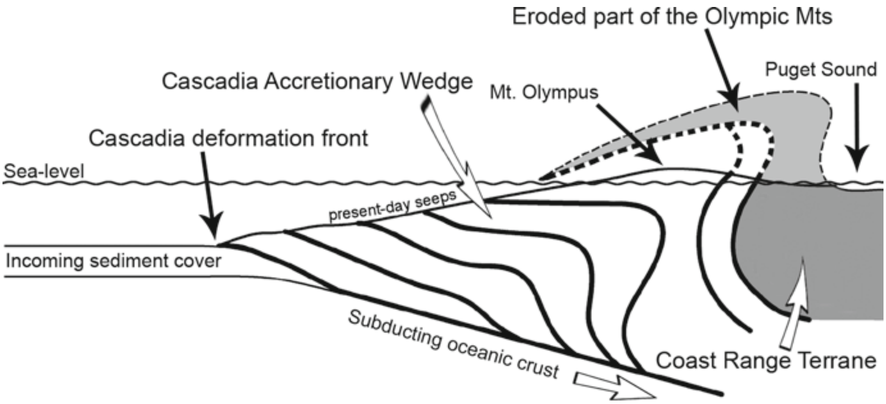

Fig. 14.2 Cross section through the Cascadia subduction zone (Redrawn from Stewart and Brandon 2004)

Mountains are uplifted, the seep-bearing sediments of the Coast Range terrane are uplifted, too. Due to ongoing erosion in western Washington, and of the Olympic Mountains in particular, the seep-bearing sediments of the Coast Range terrane are now exposed in a horseshoe-like fashion around the Olympic Mountains (Fig. 14.1).

14.3 Recognition of Fossil Seeps

The recognition of seep deposits in the fossil record is based on several lines of evidence. In western Washington, where most of the exposed sediments have been deposited in cold and deep water (as evident from foraminiferal assemblages and the abundance of glendonites), the occurrence of fossil-rich limestones within deep-water mud- and siltstones is a good first proxy for a seep deposit. This is particularly true when the limestones are dominated by taxa that are also known from modern seeps sites. This line of evidence was used to identify the first fossil seep deposits in western Washington (Goedert and Squires 1990).

Seep carbonates have several petrographic peculiarities including wavy laminations, banded and botryoidal cement, clotted micrite, and so-called yellow calcite (cf. Greinert et al. 2001; Peckmann et al. 2001) which can be recognized in fossil examples (see Goedert and Campbell [1995] and Peckmann et al. [2002] for examples from Washington State). These characteristics are often obvious even in the field, making the difference between seep carbonates and non-seep related carbonates such as concretions readily apparent. Such petrographic evidence for ancient seep deposits is often used in concert with the geochemical and biogeochemical methods described below.

Probably the most commonly used line of evidence is the carbon isotope signature of the limestone, especially of those carbonate facies that are associated with microbial methane oxidation. Methane is isotopically very light and carbonates that precipitate due to methane oxidation inherit (to some extent) this isotopic signature. This signature is usually given as the deviation of the $^{12}C/^{13}C$-ratio from the standard Vienna PeeDee belemnite (in ‰$\delta^{13}C$ PDB). Typical methane seep carbonates have $\delta^{13}C$ values of −35‰ to −60‰, those with crude oil as the main hydrocarbon in the seeping fluid have $\delta^{13}C$ values of around −20‰ to −30‰. In western Washington, carbonate $\delta^{13}C$ values were for example used in the recognition of seep deposits in the Mio-Pliocene Quinault Formation (Campbell 1992), the early Oligocene part of the Makah Formation (Goedert and Campbell 1995), and in the late Eocene to late Oligocene Lincoln Creek Formation (Peckmann et al. 2002).

A powerful tool to prove that methane oxidation occurred at putative ancient seep sites is the use of biomarkers (molecular fossils) of methane-oxidizing archaea. This method is outlined in detail in Chapter 4 of this book, and has been used in studies of seep deposits in the Lincoln Creek and Pysht Formations in western Washington (Peckmann et al. 2002; Goedert et al. 2003).

14.4 The Bear River Deposit

Prior to the discovery of Recent chemosymbiotic communities associated with vents and seeps in the deep sea (Corliss et al. 1979; Paull et al. 1984), the paleoecology of fossil bivalve-dominated invertebrate assemblages preserved in carbonate deposits in deep-marine strata was difficult to interpret. An excellent example of this is the ‘Bear River’ site, a localized, relatively small-sized limestone deposit within nearly barren Late Eocene deep-water strata, which preserved an anomalous and diverse invertebrate assemblage (Goedert and Benham 2003). The Bear River limestone deposit was reported as early as 1916 (Danner 1966 states this but does not cite the report) and was first used locally for agricultural purposes. The first detailed study of this site was an analysis of the limestone by Danner (1966), and he mentions the fossils but simply referred to the deposit as a ‘reef’. A few other reports show the Bear River locality on maps (Weaver 1937) or in lists of fossil localities (Weaver 1942) although for reasons unknown there is no mention of its fossil content. Sponge fossils from the Bear River site were described by Rigby and Jenkins (1983), but they did not discuss the associated fauna or speculate as to the paleoecology of this site. Finally, the Bear River assemblage was interpreted as an ancient cold-seep community (Goedert and Squires 1990; Squires and Goedert 1991), and this was largely on the basis of the vesicomyid and mytilid bivalve taxa that are present.

Probably the most abundant macrofossils are specimens of the mytilid *Bathymodiolus willapaensis* (Squires and Goedert 1991); they appear to make up much of the rock in hand samples, most are closed-valved and appear to be in random orientations. Specimens of the vesicomyid *Adulomya chinookensis* (Squires and Goedert 1991) are fairly common, up to 9 cm long, and in many cases they are found in clusters. Solemyids are relatively rare and most are articulated and seem to be both randomly oriented and distributed. Some large individuals are up to 13 cm long and appear to be *Acharax dalli*, a species found at many outcrops of Eocene and Oligocene strata in the Pacific Northwest. Lucinids are few but large (possibly *Cryptolucina*, up to 9 cm long) and only one small thyasirid has been found so far (Goedert and Benham 2003). Gastropods are mostly small and inconspicuous, although they are numerous and include typical extant vent and seep taxa such as *Provanna*, *Hyalogyrina*, *Depressigyra*, *Lurifax*, and two trochoids (Kiel 2006). Gastropod limpets are rare, while worm tubes are abundant.

An unusual feature of the Bear River deposit is the abundance of uncrushed fossils of the hexactinellid sponge *Aphrocallistes polytretos* Rigby and Jenkins, 1983. Hexactinellid sponges were recently reported from recent seeps offshore New Zealand where they were found in close association with seep carbonates and *Lamellibrachia* tubeworms (Baco et al. 2010). The mode of life of these sponges, however, is unclear. The hexactinellids at the Bear River deposit must at least have been able to tolerate the hydrocarbon discharge because they are abundant, large, branching and in most cases intertwined with mussels, vesicomyids, solemyids, and worm tubes. Symbioses between sponges and methanotrophic bacteria have to date only been documented for the poecilosclerid *Cladorhiza* (Vacelet et al. 1995) and a new species of demosponge (*Pseudosuberites* sp.; Thurber et al. 2009).

14.5 Humptulips Formation

The seeps of the Humptulips Formation are the oldest in the area, being of middle Eocene age (cf., Prothero 2001). Compared to the younger seep deposits in Washington they have their own distinctive character. Many of the seep carbonates were found in situ and extend laterally for several tens of meters. Some of these deposits are dominated by large, smooth lucinids of the genera *Cryptolucina* and *Nipponothracia*, which gives them a slight 'Mesozoic' character. Nevertheless, at the same seeps the earliest vesicomyids and bathymodiolins were found, though they are rare compared to the Late Eocene sites in other formations such as the Bear River deposit.

The seeps of the Humptulips Formation show distinctive faunal assemblages within individual seep deposits. Large, inflated thyasirids are commonly found in clusters of five or six; other parts of the deposit contain loosely scattered solemyids and nothing else. Tube worm clusters are usually associated with a diverse and relatively abundant gastropod fauna of neomphalids, limpets, and trochoids. In most deposits, large portions consist of wavy, laminated limestone that is entirely fossil-free. These faunal assemblages within one seep site resemble those described from modern seeps (Sahling et al. 2002; Levin and Mendoza 2007; Olu-Le Roy et al. 2007), indicating that the present-day adaptations to different chemical microenvironments at seeps already existed more than 40 million years ago. At least two seep sites in the Humptulips Formation contain numerous specimens of a large and slender gastropod, up to 90 mm high, that is an unusual genus named *Humptulipsia*

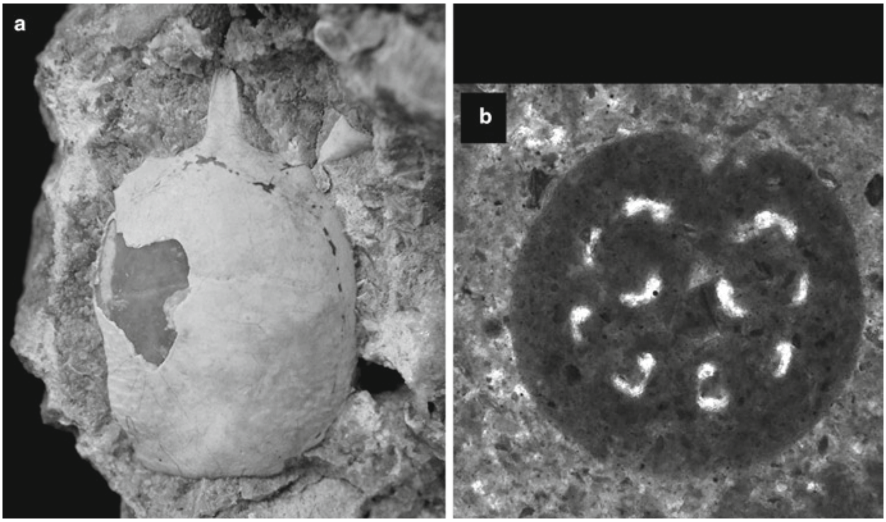

Fig. 14.3 Crustacean fossils and fecal pellets. (**a**) Carapace of the galatheid crustacean *Shinkaia katapsyxis* Schweitzer and Feldmann, 2008 from a seep deposit in the Humptulips Formation. (**b**) The trace fossil *Palaxius habanensis*, a fecal pellet probably produced by callianassid shrimp, from an early Miocene seep deposit of the Astoria Formation

that may be distantly related to provannids (Kiel 2008b). Another member of this genus has recently been identified from an early Cretaceous seep site in southern France (Kiel et al. 2010). One of these sites also preserves a neritid-like gastropod called *Thalassonerita eocenica* by Squires and Goedert (1996), which was later considered as belonging to the enigmatic vetigastropod genus *Sahlingia* (Warén and Bouchet 2001). Despite extensive subsequent sampling at this site, no new specimens that could clarify its identity have been found.

Another modern aspect of a seep in the Humptulips Formation is the recent discovery of abundant and well-preserved specimens of the galatheid crustacean *Shinkaia katapsyxis* Schweitzer and Feldmann, 2008. Its unusual mass occurrence suggests that *Shinkaia katapsyxis* (Fig. 14.3a) lived gregariously in swarms with large numbers of individuals of its own species, like its modern congener at vent sites in the western Pacific Ocean (Schweitzer and Feldmann 2008). Galatheids are not the only crustaceans at seeps in the Humptulips Formation. Peckmann et al. (2007) reported a seep deposit with several callianassid chelipeds which they were able to link to perforated fecal pellets known as *Palaxius* (Fig. 14.3b).

14.6 Lincoln Creek Formation

Sediments of the Lincoln Creek Formation (LCF) are geographically widespread, ranging from the southern slopes of the Olympic Mountains to the north shore of the Columbia River, and they contain a wide diversity of seep communities.

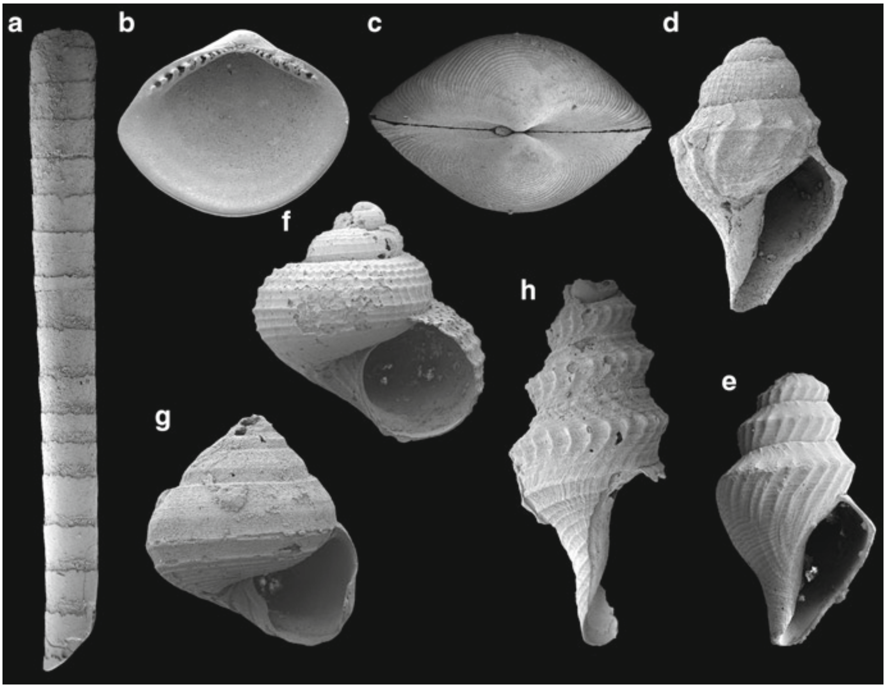

Fig. 14.4 Silicified fossils from a late Oligocene seep deposit of the Lincoln Creek Formation, found float near Knappton on the bank of the Columbia River. (**a**) Straight, segmented worm tube. (**b**, **c**) The protobranch bivalve *Tindaria*. (**d**, **e**) *Benthomangelia*, a predatory turrid gastropod, note the fine sculpture on the larval shell in c. (**f**) The trochid gastropod *Solariella*. (**g**) The seguenziid gastropod *Halystina*. (**h**) The turrid gastropod *Ptychosyrinx* (Images from Kiel 2010)

Many of the fossils found in seep carbonates of the LCF must have been enclosed in the carbonate very rapidly, because they often preserve the original mineralogy of molluskan shells, articulated specimens of polyplacophorans, as well as very delicate structures such as ornamentations of molluskan larval shells (Peckmann et al. 2002; Kiel 2006; Fig. 14.4). The preservation of original shell mineralogy is confined to seep deposits found in the area just south of the Olympic Mountains, in the Canyon and Satsop River area (Fig. 14.5; Plate 31). A seep deposit near Menlo, along the Willapa River, is poorly exposed (Goedert and Squires 1990; Campbell and Bottjer 1993) and not studied in detail but does contain abundant specimens of *Bathymodiolus willapaensis* and other bivalves. Other localities along the Willapa River are suspected to be seep deposits (Nesbitt et al. 1994; Goedert and Peckmann 2005) but have yet to be studied in detail and more field-work in the Willapa River area would undoubtedly be productive. Further to the south, along the shore of the Columbia River, fossils are mostly silicified, but the preservation of fine details is just as good as in the northern part of the Formation. Most of the deposits in the Lincoln Creek Formation are small in size, in some cases consisting of less than one cubic meter of limestone. One notable exception

Fig. 14.5 Seep deposit in the Lincoln Creek Formation, cropping out along the bank of the Satsop River; hammer for scale (site SR2 of Peckmann et al. 2002). This image was taken in 1997, the deposit has now (2009) been completely eroded away. An extended color plate of this figure can be found in Appendix (Plate 32)

to this is a deposit termed the "West Fork Satsop locality" (Campbell and Bottjer 1993) which is exposed in a cliff above the river for distance of one kilometer. The "West Fork Satsop locality" also preserves bathymodiolin mussels in large numbers, and a number of other molluskan taxa, but the deposit and fauna have yet to receive any detailed study.

Using material from the LCF (Goedert et al. 2000) proposed a model of worm tube preservation. Botryoidal aragonite precipitates on the inner and outer surface of the tube, is then engulfed by clotted micrite and finally the aragonitic material (and also the original tube wall) is replaced by silica (Goedert et al. 2000). A few sponges and corals were also found at seeps in the Lincoln Creek Formation (Peckmann et al. 2002; Goedert and Peckmann 2005). One LCF seep site yielded four different species of beautifully preserved hexactinellid sponges, two of which have yet to be reported elsewhere and were possibly endemic (Rigby and Goedert 1996). As in the Bear River deposit, these sponges must have been able to tolerate hydrocarbon discharge, because they are numerous and intertwined with worm tubes and abundant provannid gastropods. The relationship between sponges, corals and seeps in modern oceans is debated and not fully understood, thus it is notable that at least one small coral, *Deltocyathus insperatus* Goedert and Peckmann, 2005 appears to have been endemic to one seep deposit (SR4 of Peckmann et al. 2002) in the Lincoln Creek Formation (Goedert and Peckmann 2005).

Chemosymbiotic bivalves are diverse but generally neither as abundant nor as large as in the Bear River site or seeps in the Humptulips Formation. The most common vesicomyid is *Archivesica knapptonensis*, which is much smaller than the slightly older *Adulomya chinookensis* (Amano and Kiel 2007); another vesicomyid is a small (~1 cm) and rare *Pliocardia* spp. Large lucinids such as *Cryptolucina* or *Nipponothracia* are rare, most lucinids in the Lincoln Creek Formation belong to the genus *Lucinoma*. Thyasirids, solemyids and bathymodiolins are moderately common and are not different from those found elsewhere in western Washington. One small seep deposit along the Canyon River preserves a few brachiopods, possibly *Hemithyris astoriana*, along with thyasirids, solemyids, and *Lucinoma* sp.; few Cenozoic seeps worldwide are known to preserve brachiopods (Campbell 2006; Chapter 9 in this book).

Perhaps thanks to the excellent preservation, there is a high diversity of small gastropods in the seep deposits of the Lincoln Creek Formation (Squires 1995; Peckmann et al. 2002; Kiel 2006). These gastropod faunas show a marked ecologic difference between those from the northern part of the Lincoln Creek Formation and those found along the Columbia River. Whereas bacteria-grazers such as *Provanna*, *Retiskenea*, *Lurifax*, *Depressigyra*, *Hyalogyrina* and *Pyropelta* are common in the north, these groups are virtually absent from the seep deposits found along the Columbia River. Gastropods from the southern localities all belong to known deep-water genera and may be members of the background, deep-water fauna, although their ecology is not yet fully understood. Also their mode of occurrence differs: the bacteria-grazers in the northern seeps are usually enclosed in the micritic carbonate matrix, whilst gastropods in the seep deposits from the Columbia River are most abundant in patches of fine sediment trapped within the seep carbonate.

Apart from seep deposits, the LCF produced many invertebrate communities associated with sunken wood (wood-fall communities). The two most common fossils in these communities are the bathymodiolin *Idas*? *olympicus* and the patellogastropod limpet *Pectinodonta palaeoxylodia*; extant members of these two genera are commonly found on wood-falls. The overall diversity of wood-inhabiting taxa is high in the LCF, the most interesting taxa include the neomphalid *Leptogyra squiresi*, provannids, skeneids, cocculinids, two different polyplacophorans, and an ostracod belonging to *Xylocythere*, a genus that is today endemic to vents and wood-falls (Kiel and Goedert 2006a, b, 2007). Very few taxa are found in both wood-fall and seep communities in the LCF, despite the high diversity in both types of communities. Shared taxa include *Provanna antiqua*, *Leptochiton*, and general deep-sea browsers such as nuculanid bivalves and turrid gastropods (Kiel and Goedert 2006a). Further overlap might be found among the small 'skeneiform' gastropods, but their poor preservation so far precludes a detailed investigation. The two oldest whale-falls known to date (latest Eocene) are from the LCF and were found in the Satsop and Canyon River area. Associated taxa include modioliform mussels which might perhaps be bathymodiolins, and the buccinid gastropod *Colus*, which is a general predator and scavenger (Kiel and Goedert 2006a; Kiel 2008a). Modiolin mussels were also found associated with a fish skeleton in the LCF (Kiel 2008a).

14.7 Makah and Pysht Formations

These two formations are late Eocene to early Miocene in age, consist mainly of bathyal deposits, and are best exposed along the shore of the Juan de Fuca Strait on the north side of the Olympic peninsula. Seep deposits are known from late Eocene to early Oligocene strata and can be found as erosional lag materials along beach exposures, as well as in situ within deep water siltstones, especially east of the mouth of the East Fork of Twin River, in Clallam County. Only two sites have been investigated in detail so far, but several more have been sampled and await description. Goedert and Campbell (1995) reported an early Oligocene seep deposit from Shipwreck Point in the Makah Formation. It included a diverse assemblage (25 taxa) including *Bathymodiolus willapaensis*, vesicomyids, lucinids, *Acharax* sp. of up to 75 mm length, *Provanna antiqua*, small, globular gastropods resembling hyalogyrinids or *Retiskenea*, several turrid and trochid gastropods, plates of the polyplacophoran *Leptochiton*, as well as worm tubes, shrimp remains (cf. *Callianassa*) and scaphopods (Goedert and Campbell 1995). The other well-studied seep deposit is from the late Eocene part of the Pysht Formation at the mouth of Whiskey Creek (Goedert et al. 2003; Peckmann et al. 2003). The fauna includes large lucinids, vesicomyids, bathymodiolins, thyasirids, *Acharax*, and a few poorly preserved gastropods and worm tubes. Biomarker studies revealed the presence of crocetane, biphytane and squalane strongly depleted in ^{13}C ($\delta^{13}C$ values as low as −101‰), indicating that methane oxidation by archaea was a significant carbon source at this site (Goedert et al. 2003). Pyrite with ^{34}S-depleted sulfur indicates that bacterial sulfate reduction was the sulfide-generating process at this site, supplying the abundant bivalves with sulfophilic symbionts with nutrients (Peckmann et al. 2003).

In the Murdock Creek area (Pysht Formation) seep limestone contains thyasirid, solemyid, modiolid, and vesicomyid bivalves (Goedert and Squires 1993). Other invertebrate taxa have been found as well, including gastropods and echinoids, crinoid fragments, as well as small blocks of seep limestone with abundant, relatively large (up to 20 mm length) nuculanid bivalves. In outcrops near the Twin Rivers seep limestones are exposed as small pods, up to 1.5 m across, many containing specimens of thyasirid bivalves up to 75 mm long and 50 mm wide (J.L. Goedert and S. Kiel 2010).

The Makah and Pysht formations are renowned for their whale- and wood-fall communities (Squires et al. 1991; Goedert et al. 1995; Lindberg and Hedegaard 1996; Kiel and Goedert 2006a). Taxa associated with wood-falls are essentially the same as described for the Lincoln Creek Formation (Kiel and Goedert 2006a). The whale-fall communities of the Makah and Pysht formations are mostly of upper early Oligocene age and thus stratigraphically younger than those of the LCF. The species diversity in the Makah and Pysht whale falls is higher than in the LCF. There are two species of bathymodiolin mussels, thyasirid and lucinid bivalves occur, as well as predatory gastropods such as naticids, buccinids, and cephalaspideans.

14.8 Astoria Formation

Deep-water sediments of the early to middle Miocene Astoria Formation crop out along the Columbia River, to the east of the Lincoln Creek Formation (Wolfe and McKee 1968, 1972; Wells 1989). Seep carbonates found so far are mostly small float blocks from the foot of landslides, but some thin (up to 10 cm thick) lens-like seep carbonates have been found in situ. There are no whale- or wood-fall communities yet. Two types of seep deposits have been found so far. In one of them, thin sections show few if any typical seep carbonate structures but are of the ‘mudstone’ type sensu (Greinert et al. 2001). The fauna of these deposits is of low diversity, but the fossils are silicified and often remarkably well preserved. They were first mentioned when Amano and Kiel (2007) described the small vesicomyid bivalve *Isorropodon frankfortensis* from them. The remaining fauna includes a few worm tubes, a possible member of the heterobranch gastropod *Hyalogyrina*, and a few neogastropods and opisthobranchs. The other type of seep carbonate contains cements and pyrite, and a diverse mollusk fauna whose shells are recrystallized to calcite. There are several chemosymbiotic bivalves including an undescribed vesicomyid of moderate size, resembling *Pliocardia*, a common thyasirid, and few solemyids (see Plate 32d for example). Mytilids and lucinids have not been found so far. Gastropods include many predatory neogastropods and opisthobranchs, a few small provannids, but no skeneiform bacteria-grazers (Kiel 2010).

14.9 Further Seeps

Other seep sites are known in other rock units, but have not been studied in detail as of yet. Some seep carbonates have been recognized in Eocene deep-water rocks mapped as “Unit B” (cf., Wolfe and McKee 1968) on the West Fork of Grays River, upstream from the mouth of Beaver Creek. Poorly preserved vesicomyid bivalves have been found, along with possible solemyid and thyasirid fragments (J.L. Goedert and S. Kiel 2010).

Large limestone blocks displaying wavy, laminated structure and containing fossils of modiolid and solemyid bivalves, small gastropods and worm tubes are exposed on the beach along the shore of the Columbia River near the townsite of Knappton (Goedert and Benham 2003; Plate 32a). These limestone blocks are apparently derived from Eocene rocks called “siltstone of Shoalwater Bay” by Wells (1989).

Within rocks of the Olympic Structural Complex is a limestone lense, poorly exposed and probably Oligocene in age, near Mt. Appleton. Fossils of bivalves were collected in 1940 and the assemblage contains solemyids, thyasirids, and vesicomyids according to the late Ralph Stewart, U. S. Geological Survey (Harvey 1959). This locality was visited briefly by J. L. Goedert in 1994 and only a few fossil bivalves were collected, but they are too poorly preserved to be identified. A sample of the limestone was analyzed by J. Peckmann and he confirmed that the site is an ancient seep site. Another seep site from the Olympic Structural Complex was described by Campbell (1992) from the Mio-Pliocene Quinault Formation, and includes solemyid and thyasirid clams, and as-yet unidentified modiolin mussels.

14.10 Conclusions and Outlook

The rich and well-preserved record of fossil seep and other chemosynthetic communities make western Washington an excellent starting point for evolutionary and ecologic studies on geologic timescales. Seep communities with a stratigraphic range from the middle Eocene (~40–45 million years) to the Mio-Pliocene (~5 million years) have produced many oldest records of extant vent and seep taxa, including major groups like vesicomyids and bathymodiolins, galatheid crabs, and also many minute gastropods. The relatively robust paleobathymetric framework based on extensive studies of benthic foraminifera provides insights into the role that water depth had on shaping seep communities in the geologic past: there is a general trend of an increasing proportion of background species, non-symbiotic bivalves and predators in particular, towards the shallower sites (Kiel 2010). Apart from large-scale evolutionary and ecologic trends, ecologic differentiation can be seen in individual sites. Distinct communities within larger seep sites are known for example in the Humptulips Formation (Goedert and Squires 1990). The potential geochemical reasons for such differentiation, as shown in a pioneering study of a Cretaceous seep site in Japan (Jenkins et al. 2007), makes an interesting focus of future studies. This is particularly the case because molecular fossils (biomarkers) are usually well-preserved and abundant in the seep deposits of western Washington (Peckmann et al. 2002; Goedert et al. 2003; Hoffmann 2006); however, many more sites await detailed analysis. More than 65 invertebrate species from around 30 seep sites in western Washington have been dealt with in about 25 papers, and more new species have been recognized but await description (Kiel 2010). Much more work remains to be done, even in this region where ancient seep sites are well studied.

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