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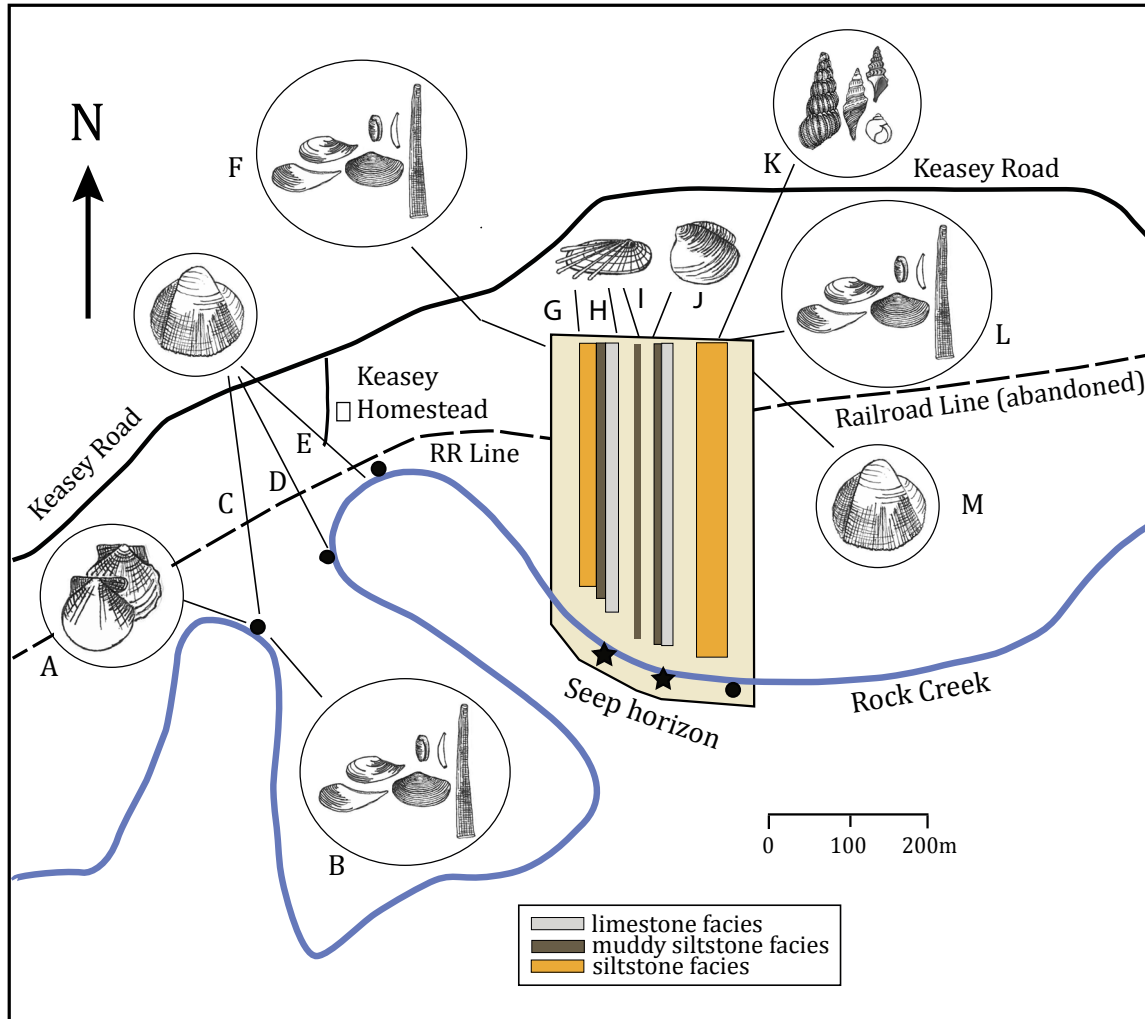
David G. TAYLOR, Carole S. HICKMAN, Elizabeth A. NESBITT, Kathleen A. CAMPBELL and Ruth A. MARTIN (2023).
A methane seep from the deep-marine, late Eocene Keasey Formation, Rock Creek, Columbia County, Oregon

A methane seep from the deep-marine, late Eocene Keasey Formation, Rock Creek, Columbia County, Oregon

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Investigation of a deep-water carbonate seep complex in the late Eocene Rock Creek section of the Keasey Formation, northwestern Oregon State, provides new data on marine carbonate seep occurrences in the formation. The Rock Creek seep described here, together with the previously described Vernonia-Timber Road seep and Crinoid lagerstätte at Mist expands the Keasey Formation methane seep signatures. These three sites illustrate different points on a continuum from effusive to diffusive expulsion of methane and biotic chemosynthetic activity. Lithologic descriptions include a richly fossiliferous carbonate body named the Main Seep Site, carbonate pipes interpreted as flow conduits comprise the Second Site, and minor pockets of blebby nodules is the Third Site, all within a 35 m stratigraphic section. Lithologic facies contain six named and characterized mollusk associations. Two are low-diversity with recognized chemosymbiotic bivalves and four contain opportunistic taxa tolerant of toxic geochemistry, severe oxygen depletion and nutrition potentially based on chemosynthetic microbial productivity. Analysis of O and C isotopes from the carbonate rock and from benthic foraminifera indicate that the methane-charged fluid flowed through sedimentary layers and probably burrows, and was driven by sustained microbial anaerobic oxidation of methane.

Keywords: Cascadia, seep carbonates, chemosynthesis, chemosymbiosis, mollusk associations, Siletzia

INTRODUCTION

Continental shelves and slopes are highly productive settings, with an estimated 80% accumulation of the ocean's total organic carbon (Smith and Hollibaugh 1993, Wollast 1998, Ver et al. 1999). Sedimentation rates and biological productivity are higher along coastal zones of the ocean than in other regions (Suess 2014). Periods of elevated global temperatures, for example during the Paleocene and Eocene, have resulted in increased productivity and the sequestration of organic matter in coastal marine sediments generating hydrocarbon reserves. Sediment compression by tectonic events and overlying deposition forces the low-density hydrocarbons, mostly methane, within the sedimentary sequences to migrate to the sediment-water interface to generate hydrocarbon seeps (Moore and Vrolijk 1992). Along the modern Washington and Vancouver Island coast only 30% of the active methane release sites are below 250 m and measured flow rates vary widely (Riedel et al. 2018). Hydrocarbon seepage, documented throughout the history of the

Cascadia margin from middle Eocene onwards, is recognized from a variety of seep-specific fossiliferous sites interpreted to be from shallow to bathyal paleo-depths (e.g., Kiel 2010, Jakubowicz 2020, Hryniewicz 2022). Anaerobic oxidation of methane, mediated by archaea and sulfate-reducing bacteria, leaves distinct biogeochemical signatures of both methanotrophy and methanogenesis in carbonates formed at seepage sites (e.g., Naehr et al. 2007, Knittel and Boetius 2009, Suess 2014). These signatures are retrievable from the fossil record of cold methane seeps along ancient continental margins (e.g., Peckmann et al. 2002, Campbell 2006, Miyajima et al. 2016). Cold methane seeps sustain unique chemosynthesis based ecosystems at the seafloor, sometimes referred to as the "hydrocarbon-metazoan-microbe-carbonate association" (Suess 2014, Feng et al. 2018).

Many fossil hydrocarbon seep deposits have been recognized in Jurassic to Pliocene forearc strata along the margin western North America, in a north-south trending zone of tectonic plate convergence (Campbell 2006). Within this setting is a remarkable temporal and paleogeographic cluster of fossil cold seeps from the late Eocene through early Miocene in western Washington and northwestern Oregon states, U.S.A. and Vancouver Island, British Columbia Province, Canada, that correlates with establishment of the Cascadia forearc and onset of Cascade volcanism (e.g., Goedert and Squires 1990, Campbell and Bottjer 1993, Goedert and Campbell 1995, Campbell 2006, Kiel and Amano 2013, Nesbitt et al. 1994, 2013, Hryniewicz 2022). This Paleogene seep cluster also correlates with a dramatic marine faunal turnover at the culmination of global cooling between 43 and 33.5 Ma and the appearance of novel seep communities dominated by chemosymbiotic mollusks (Hickman 2003, 2018).

The geological expression and biological assemblages at the sediment surface vary as advecting fluid flux and composition vary. Fluid pathways and the spatial extent of seepage, as well as carbonate cement sealing and conduit-fill with cement influence the expression, size, and longevity of the hydrocarbon seepage at the surface and within the sediment pile (e.g., Peckmann et al. 2002, Campbell 2006, Nyman et al. 2010, Miyajima 2016, 2018, Meehan and Landman 2016, Nelson et al. 2019).

The fossil seep records in Oregon and Washington encompass a broad range of geological structures, from large carbonate mounds with extensive subsurface plumbing systems to areas with only scattered centimeter-sized carbonate blebs, nodules, and small burrow fills, the latter of which are termed diffuse seep carbonates (e.g., Goedert and Squires 1990, Campbell 1992, Goedert et al. 2003, Peckmann et al. 2002, 2007, Martin et al. 2007, Nelson et al. 2019). Hickman (1984) identified the existence of an unusual paleoenvironment in sedimentary strata of the Eocene-Oligocene transition in the Pacific Northwest with recognition of fossil communities dominated by lucinid, thyasirid and solemyid bivalves in the Keasey Formation before their hydrocarbon seep affiliation was known. These taxa became part of a "seep-search strategy" (Campbell and Bottjer 1993) that has led to discovery and documentation of seep carbonate occurrences across the Cascadia forearc (Campbell 2006, Kiel 2010, Hryniewicz 2022). Seeps are characterized by distinctive and recurring petrographic features and fabrics, fluid conduits, and taxa characteristic of modern seep and hydrothermal vent environments (e.g., *Calyptogena* Dall, 1891, *Acharax* Dall, 1908, and *Provanna* Dall, 1918), as well as preservation of distinctive carbon stable isotopic signatures of methane-rich fluids (e.g., Peckmann et al. 2002, Goedert et al. 2003, Martin et al. 2007).

The purpose of this paper is to describe seep carbonate deposits and fossils within a thick siliciclastic sequence exposed along the banks of Rock Creek, near Vernonia in Columbia County, Oregon (Fig. 1) within the middle member of the Keasey Formation (Campbell and Bottjer 1993, Nesbitt et al. 2006, Hickman 2015). This provides a substantial descriptive approach characterizing not only the seep deposits themselves, but furnishing a detailed account of the lithostratigraphy and associated molluscan faunas throughout a 35 m stratigraphic interval. This is the first account of a detailed stratigraphic column in the Keasey Formation and its contained macrofauna. Thus, the description of the "background non-seep-related" faunas provides an appreciation of the dissimilarities with faunas within the seep deposits themselves.

The hitherto undescribed Rock Creek seep carbonates and associated chemosymbiotic fauna, as well as two additional sites in the Keasey Formation, the Timber-Vernonia seep (Campbell and Bottjer 1993) and the famous crinoid lagerstätte at Mist (Burns et al. 2005) all occur within 25 km of each other and within a narrow stratigraphic range. These three outcrops illustrate different points on a continuum from effusive to diffusive expulsion of methane, chemosynthetic activity, and biological opportunism in geochemically challenging environments. The seep outcrop area on Rock Creek consists of a fossiliferous carbonate mound, a subsurface
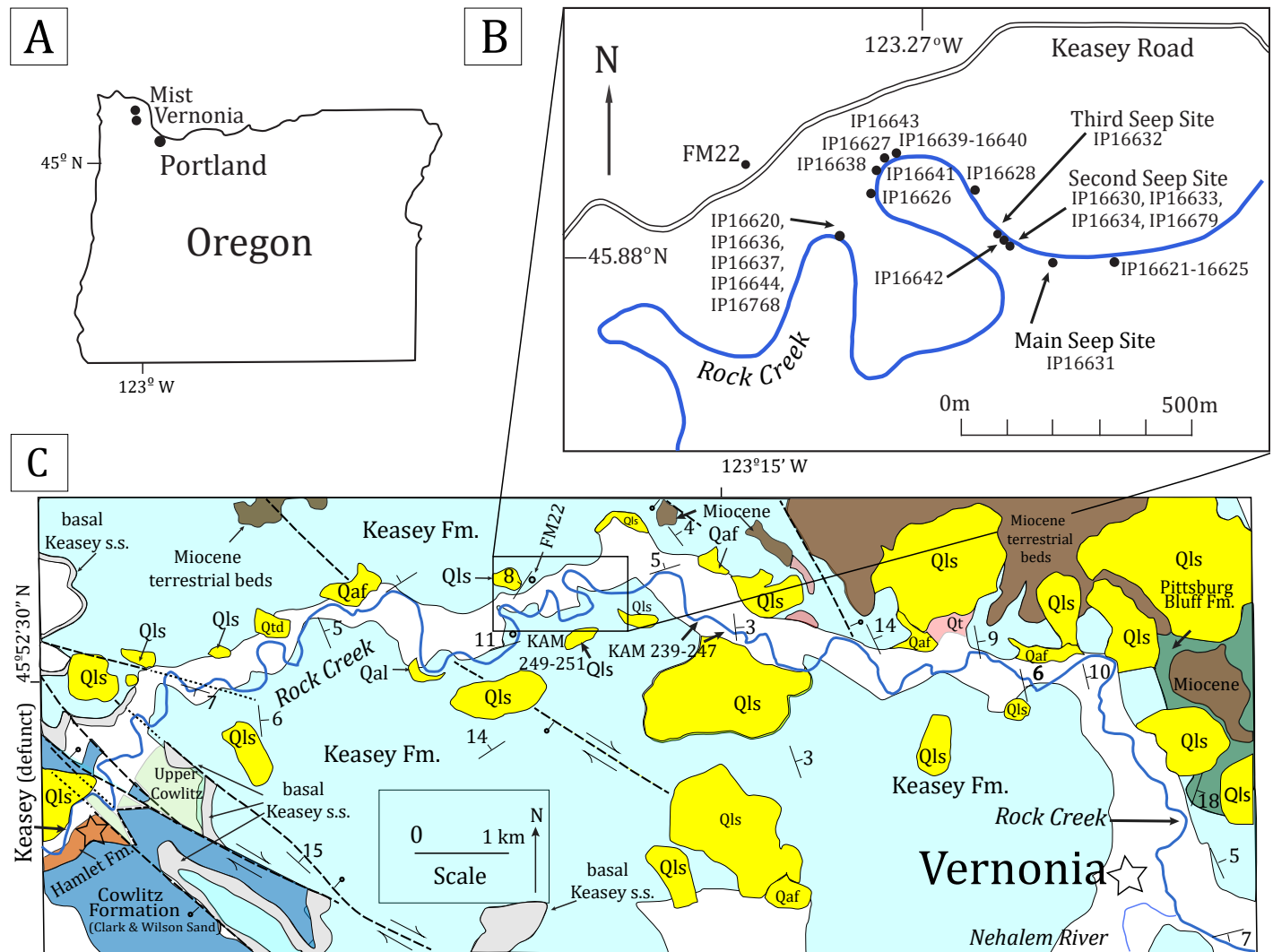
Figure 1. . Field area maps. **A.** Study site location in the vicinity of Vernonia, northwest Oregon State, U.S.A. **B.** Detail of UCMP IP localities along Rock Creek 8 kilometers west of Vernonia. UCMP IP locality 16636 at the west end is from the base of the measured section (Fig. 2) while UCMP IP locality 16621 is from the top of the measured section. The Main Seep Site is located between collections UCMP IP localities 16630 and 16621. **C.** Geologic map along Rock Creek from Vernonia to the former town of Keasey. Geology generalized from mapping by Alan Niem in Wells et al. (2020). Abbreviated geologic units in the map include the following: Qaf = Holocene and Pleistocene alluvial fan deposits; Qls = Holocene and Pleistocene landslide deposits; Qt = Holocene and Pleistocene talus; Qtd = Holocene and Pleistocene terrace deposits. M22= macrofauna locality from Warren et al. (1945) and benthic foraminiferal localities 249-251 and 239-247 from McDougall (1979).

carbonate conduit 75 m to the west, and a more diffusive carbonate signature consisting of blebby nodules 55 m west of the latter. The macro-invertebrate assemblages and benthic foraminifera from adjacent non-seep sedimentary rocks are characteristic of the Refugian Stage, latest Eocene (Priabonian) or straddling the Eocene-Oligocene boundary (McDougall 1979, 1980, Nesbitt et al. 2006, Martin et al. 2007, Hickman 2003a, 2014, 2015).

MATERIALS AND METHODS

Macrofaunal Collection

The macrofauna in the study area includes small-scale concentrations of small specimens. But predominantly, specimens are widely scattered and larger specimens are sparse. Therefore, collection of bulk samples is not feasible for semiquantitative paleoecologic analysis or characterization of faunal associations. Collections, as

a result, were obtained by collecting individuals (and small-scale concentrations) as we found them along bedding, ranging up to a lateral distance of 15 m. The faunal association should, in that case, be taken as the co-occurrence of species typically found together. There was no rigorous attempt to infer meaningful relative abundances of species.

Carbonate Isotope Analytic Procedures

Carbonate powders from fresh sawn samples of the carbonate body rocks were obtained using a microdrill. Most of the carbonate samples constitute a nodular, medium to dark gray microcrystalline carbonate that is mainly mottled and, in places, brecciated and rece-mented, containing some to no macrofossils. Samples were analyzed for C and O isotopes on a Thermo Advantage stable isotope ratio mass spectrometer (IRMS; Thermo, Bremen) by Iso-Trace NZ Limited. Carbon and oxygen isotope ratios were measured by reaction with 4-5 drops of 105 % of anhydrous phosphoric acid to form carbon dioxide. Acid and carbonate were reacted for 18 hours at 25.00 ± 0.01 °C. Standard carbonates and test samples were weighed to 200 ± 20 μg to ensure that all tests provided similar signal intensity. Isotopic compositions were determined from international standards (NBS-18, NBS-19, LSVEC) and an internally characterized laboratory standard (IRU-Marble). Sample masses were recalculated based on carbonate proportion to consistently yield 200 mg of carbonate and as such, no mass dependence corrections were applied. Replicate analysis of in-house reference materials Atlantis3 and Estremoz marine carbonates (for $\delta^{13}C$ and $\delta^{18}O$) and LVSEC (for $\delta^{13}C$) provide precision estimates of ±0.11, 0.01, and 0.02 $\delta^{13}C_{VPDB}$ ‰ and ±0.03 and 0.00 $\delta^{18}O_{VSMOW}$ ‰, respectively. All standard data are provided in Table 1.

Stable Isotope Analysis based on foraminifera

Samples used in foraminiferal analyses were collected from the Primary Seep Site, from sediment immediately adjacent to the carbonate body (University of Washington Burke Museum locality B7272). Individual foraminifera were picked from dried sediment samples and cleaned ultrasonically before being analyzed for stable isotopes. Isotope analyses were conducted in the University of Washington Department of Earth and Space Sciences Isotope Laboratory on a ThermoScientific Kiel III carbonate device attached to a ThermoFinnigan DeltaPlus IRMS. Based on multiple analyses of standards, precision was 0.06‰ for $\delta^{18}O$ and 0.03‰ for $\delta^{13}C$ relative to the PDB standard where d = (R sample /R standard – 1)1000. The difference between maximum and minimum isotopic values (e.g., $\delta^{13}C_{Max}$ - $\delta^{13}C_{Min}$) is designated by $\Delta^{13}C$.

Repository of paleontological material

University of California, Invertebrate Paleontology (UCMP IP) numbers have been assigned to all the localities collected for this paper and included in the UCMP database.

TECTONIC SETTING

Cenozoic rocks of western Oregon and Washington states, and southwestern Vancouver Island, accumulated on the basaltic basement of the early Eocene Siletzia Large Igneous Province (LIP). Siletzia formed just off-shore of western North America atop the mid-oceanic ridge between the Resurrection and Farallon oceanic plates beginning about 56 MA and subsequently was accreted to North America about 50 Ma (Haeussler et al. 2003; Wells et al. 2014; Eddy et al. 2017). Siletzia also is considered a tectonostratigraphic terrane, since the LIP was accreted. At the time of accretion an inboard subduction zone was abandoned and a new one, called Cascadia, formed to the west, outboard of the terrane. The Siletz LIP then became the basement complex of the newly established Cascadia forearc. Voluminous marine sediments (Wells et al. 2014) were deposited on the basement. Those sediments, consisting of both shallow and deep marine facies interfingered to the east with the Cascade volcanic rocks along the eastern margin of the forearc basin (Niem et al. 1994, Wells et al. 2020). The Keasey Formation is part of that Cenozoic depositional

Table 1. Isotope standards used in rock analyses.

Standard	d^{13}C$_{(VPDB)}$, ‰	d^{18}O$_{(VPDB)}$, ‰	Mineral
NBS-18	-5.01 ± 0.03	-23.01 ± 0.22	Calcium carbonate
NBS-19	1.95 ± 0	-2.20 ± 0	Calcium carbonate
IRU-Marble	2.10 ± 0.06	-2.64 ± 0.09	Calcium carbonate
VPDBBB	1.37 ± 0.03	0.30 ± 0.06	Calcite
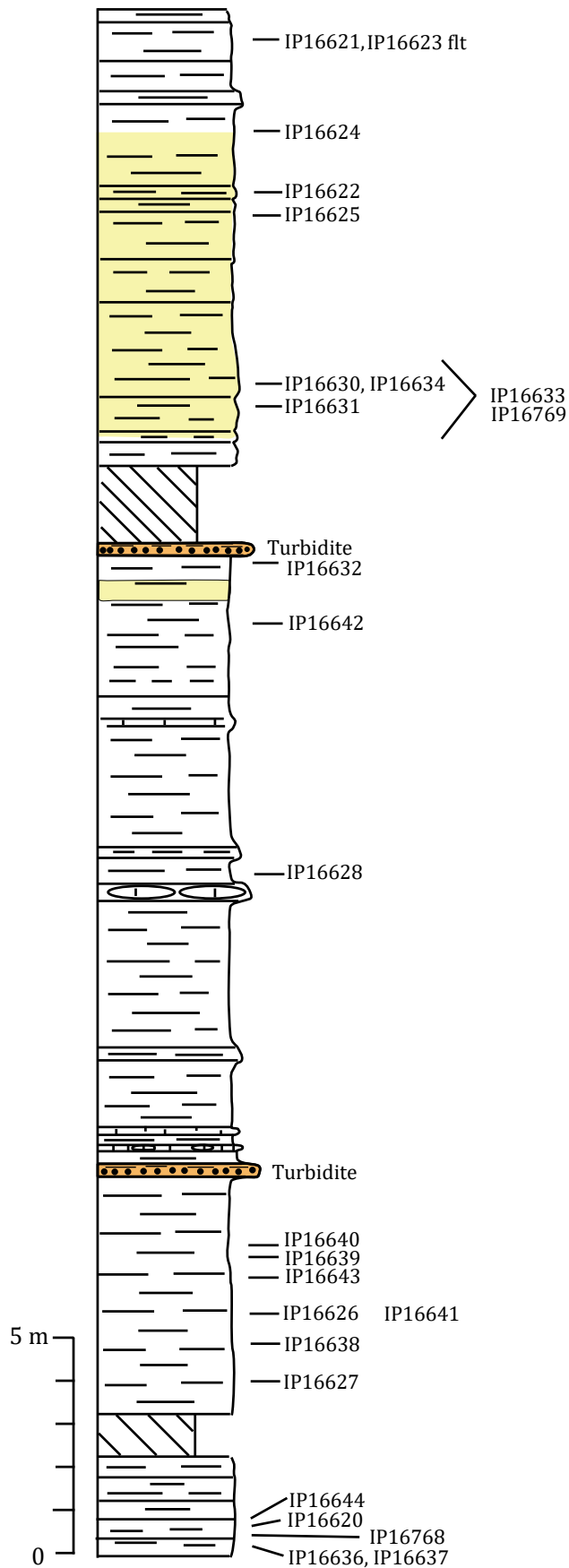
package that accumulated within a retro-forearc basin (Mannu et al. 2017, Jakubowicz et al. 2020).

The Cascadia forearc has two components, an outboard accretionary wedge (=subduction wedge) and inboard component delimited by Siletizia LIP and upon which retro-forearc basins were formed (Mannu et al. 2017, Jakubowicz et al. 2020). The Olympic Mountains uplift in the Miocene provides the one location from Oregon northward to Vancouver Island where the structurally subjacent accretionary wedge deposits have become exposed (Brandon et al. 1987, Stewart and Brandon 2004, Jakubowicz et al. 2020). Most of the Eocene sediments, therefore, represent retro-forearc deposits, in which those of the Keasey Formation are included. It is the retro-forearc sediments in which Paleogene methane seep deposits have been found in the Cascadia forearc, whereas only one has been described from the accretionary wedge deposits, in the Olympic Mountains (Kiel 2010).

THE KEASEY FORMATION AND ITS MEMBERS

The Keasey Formation, defined by Schenck (1927), consists of marine tuffaceous siltstones and mudstones deposited in the Cascadia forearc and it is presumed that much of the siliciclastic debris was derived from the Cascade volcanics (Wells et al. 2020). Keasey rocks overlie the middle Eocene marine sedimentary Cowlitz Formation, and are overlain by the marine fossiliferous Pittsburg Bluff Formation. Historically, three informal units, the lower middle and upper members, have been recognized for the Keasey Formation (Warren et al. 1945, Warren and Norbisrath 1946, Van Atta 1971). These members also yield diagnostic molluscan faunas that are consistent with the three-fold lithological division for the formation (Warren and Norbistrath 1946, Hickman 1980). Recent mapping of the Portland, Tualatin, and part of the Nehalem basins, northwestern Oregon, included naming of six informal lithologic units (Wells et al. 2020). One of those new units occurs near the defunct town of Keasey (Fig. 1) and was termed the "basal member" (Wells et al. 2020). It is a 20-80 m thick sandstone unit that Wells et al. (2020) attribute to the lowermost

Figure 2. Stratigraphic section of the Keasey Formation in the vicinity of the Rock Creek seep site, showing position of UCMP localities. Yellow highlighted area above the upper turbidite bed is the equivalent stratigraphic positions of the Main and Second Seep Sites, whereas the minor yellow highlighted area just below the upper turbidite gives the stratigraphic position of small blebby concretions defining the Third Seep Site.

Figure 3. The Main Seep Site, east side, looking west. The numbers denote the top (1) and base (2) of the seep limestone body, respectively. The limestone is covered at top by approx. 1.8 m of Keasey mudstone, typical of middle member lithology..

part of the Keasey Formation which overlies the Cowlitz Formation with slight angular discordance locally. Wells et al. (2020) used this terminology to replace the historically recognized lower member. For the study presented here, the lower, middle and upper members of the Keasey Formation of Warren et al. (1945) are used. Exposures of the lower member along Rock Creek and adjacent logging roads comprise the original type locality for the Keasey Formation (Schenck 1927). Subsequently, higher beds were included in the formation by Weaver (1937), Warren et al. (1945), and Warren and Norbisrath (1946). The basal sandstone of Wells et al. (2020) at Rock Creek has not been observed, perhaps because the unit was cut out in the vicinity of the creek by faulting.

The Keasey Formation along Rock Creek is approximately 700 m thick and the lower member is approximately 150 m thick. It consists of well-stratified and commonly laminated siltstone and interbedded mudstone with glauconitic horizons and tends to be highly micaceous (Van Atta 1971). The superjacent middle member, approximately 500 m thick along Rock Creek, is composed of light-gray, tuffaceous siltstone and mudstone beds. The seep carbonate bodies are located within the lower part of the middle member. In particular, the beds in the upper part of the middle member appear massive as a result of thorough bioturbation. The member includes numerous concretionary horizons and is exposed along Rock Creek from a short distance west of the study site to Vernonia to the east (Fig. 1). The upper member of the Keasey Formation, exposed in the vicinity of Vernonia and to the south approximately along state highway 47, consists of 50 m of well-bedded, alternating light and dark gray tuffaceous siltstone and mudstone, and is characterized by numerous well-cemented
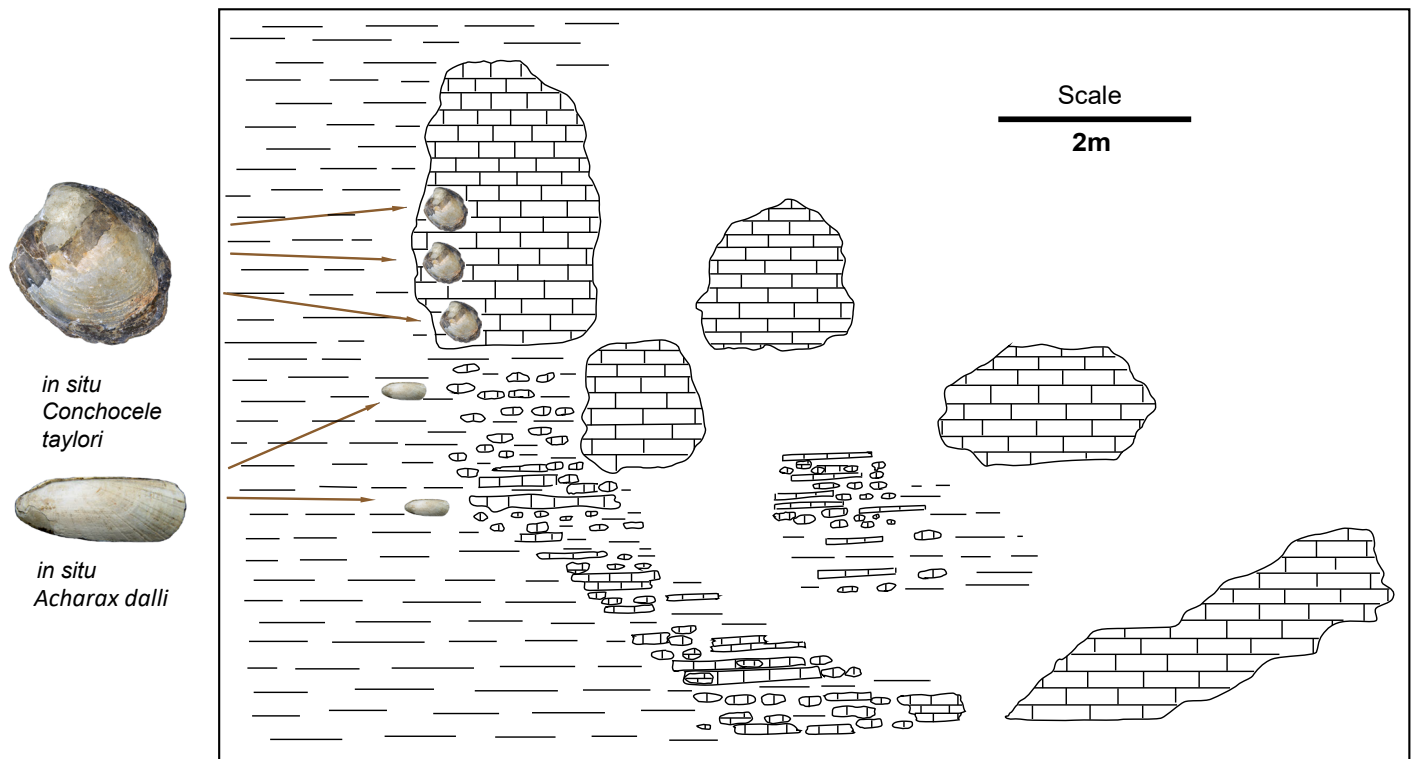
Figure 4. Sketch of the Main Seep Site in east-west cross-sectional view. The sketch shows some representative positions of primary seep-related bivalves. Note relative positions of massive limestone in relation to areas dominated by nodules and carbonate blebs. Dashed symbol represents Keasey mudstone. A meter or more of black mudstone immediately subjacent to the limestone yield seep-related mollusks.

calcareous horizons and concretionary siltstones, and the Vernonia-Timber fossil seep site (Nesbitt et al. 1994, Hickman 2015).

The bedding of the Keasey Formation along Rock Creek generally dips gently to the east, although as a result of shallow dips and gentle folding there tends to be a broad scatter of bedding orientations. While there are extensive landslide deposits along Rock Creek the succession along the measured section within the incised Rock Creek is not disrupted by these features.

AGE AND CORRELATION

Full assessment of the Rock Creek methane seep requires chronological determination and correlation with strata on the Cascadia Margin and in California. This is especially important because the Keasey Formation in northern Oregon, and the coeval Lincoln Creek Formation in southern Washington provide an early record of subduction on the new active tectonic margin. It is difficult because there are only two radiometric dates from the Keasey Formation, and they are not well constrained as to their position within the formation. These are detrital U/Pb zircon dates. One is from the middle member and gives an age of 36.10 +/- 0.43 Ma and the other is from a

tuff bed within the informal Stimson Mill member giving a date of 36.69 +/- 0.16 Ma. As a result, our correlations are based on biostratigraphic units which, however, offers complication as they may be time-transgressive.

Schenck (1927) assigned the Keasey Formation to the Oligocene based on both foraminiferal and mollluscan taxa. Weaver (1937) designated a threefold stratigraphy of the Oligocene marine rocks of western Washington and northwestern Oregon. However, he used formational names for what he described as biozonal stages. In the first biostratigraphic correlation of marine formations along western North America, Weaver et al. (1944) used the name Keasey to erect a biostratigraphic stage for the lowermost Oligocene in Oregon and Washington. Utilizing both macro- and microfossils, they assigned the Keasey, Bastendorff (Bassendorf Shale), Toledo (now part of the Alsea), lower Lincoln Creek and Townsend Shale formations to the Keasey Stage.

Keasey Formation deposition includes latest Narizian and Refugian benthic foraminiferal stages (McDougall 1979, Nesbitt 2018). McDougall (1979, 1980) provided a benthic foraminiferal succession for the Keasey Formation along Rock Creek, with the section beginning near the defunct town of Keasey and trending upsection and
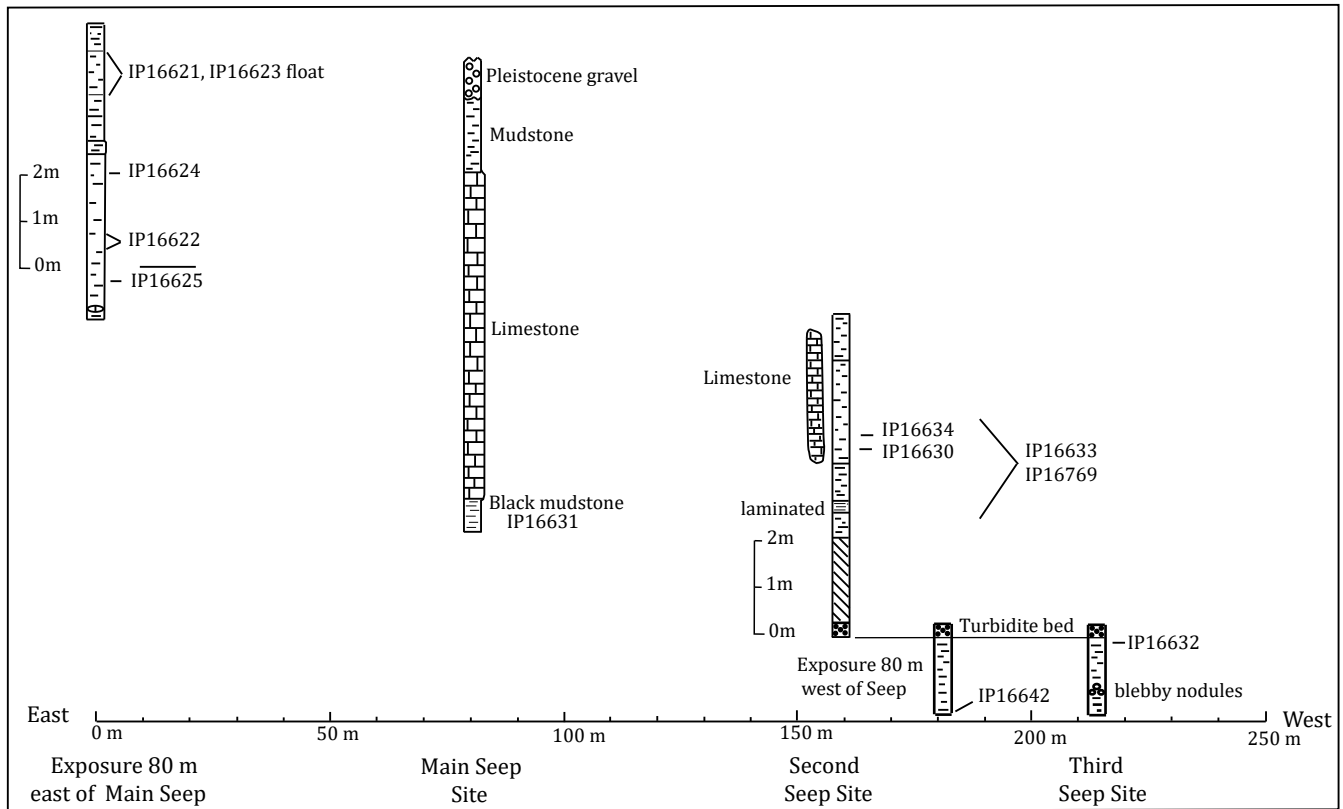
Figure 5. Stratigraphic sections of the Main Seep Site in relation to Second and Third sites and stratigraphic position of UCMP localities. The Main Seep Site (Fig. 4) consists of a thick limestone lithosome including immediately subjacent black mudstone. The Second Seep Site about 70m west of the main seep, consists of a large conduit about 0.5 m wide by 3 meters high and a complex association of concretions. This site occurs at the east end of the exposure shown in Fig. 7. The Third Seep Site includes a localized concentration of small blebby concretions.

eastward to Vernonia and she suggested that the section was deposited in upper bathyal to outer neritic depths. McDougall (1979) sampled foraminifera from three localities KAM 249 – KAM251 (Fig. 1) positioned stratigraphically below and close to the seep site and our section (Fig. 2), as well as localities KAM 239-247 stratigraphically above the study location (Fig. 1). Chronologically diagnostic species within the KAM249-251 through KAM 239-247 interval include: *Quinqueloculina imperialis* Hanna and Hanna, 1924, *Hoeglundina eocenica* Cushman and Hanna, 1927 and *Gaudryina alazaensis* Cushman, 1936, which have ranges restricted to the Refugian Stage. However, subdivision of the Refugian Stage is not feasible along Rock Creek. Taxa from siltstone sediments immediately adjacent to the seep carbonates included *Uvigerina cocoaensis* Cushman, 1925 species group*, Globobulimina pacifica* Cushman, 1927, *Nonionella stella* Cushman and Moyer, 1930 and *Cassidulina crassipunctata* Cushman and Hobson, 1935. These taxa are consistent with a placement in the Refugian *Sigmomorphina schenki* Zone *sensu* Rau (1981). In California, McDougall (2008) placed the

Refugian Stage in global planktonic foraminiferal zones P16 and P17. Cenozoic benthic foraminiferal zones are time transgressive along the northeastern Pacific margin and application of California benthic foraminiferal stages is increasingly unreliable the farther north the localities (McDougall 2008, Nesbitt et al. 2010).

 The mollusk fauna documented here is consistent with the allocation the entire section within the middle member of the Keasey Formation (Fig. 2). A molluscan biochronology for northwestern Oregon and western Washington was erected by Durham (1944) and modified by Armentrout (1975, 1981), who included six Oligocene megafossil biozones. The oldest biozone, *Turricula columbiana* zone (later name *Bathybembix columbiana* zone) was defined from molluscan fossils collected from Rock Creek, Keasey Formation and from the lowest Lincoln Creek Formation exposed along the Willapa River, near Holcomb, Pacific County, Washington.

 Armentrout (1975, 1981) erected the Galvinian molluscan stage, and the *Bathybembix columbiana* biozone comprised the lowermost part of the stage. The overlying
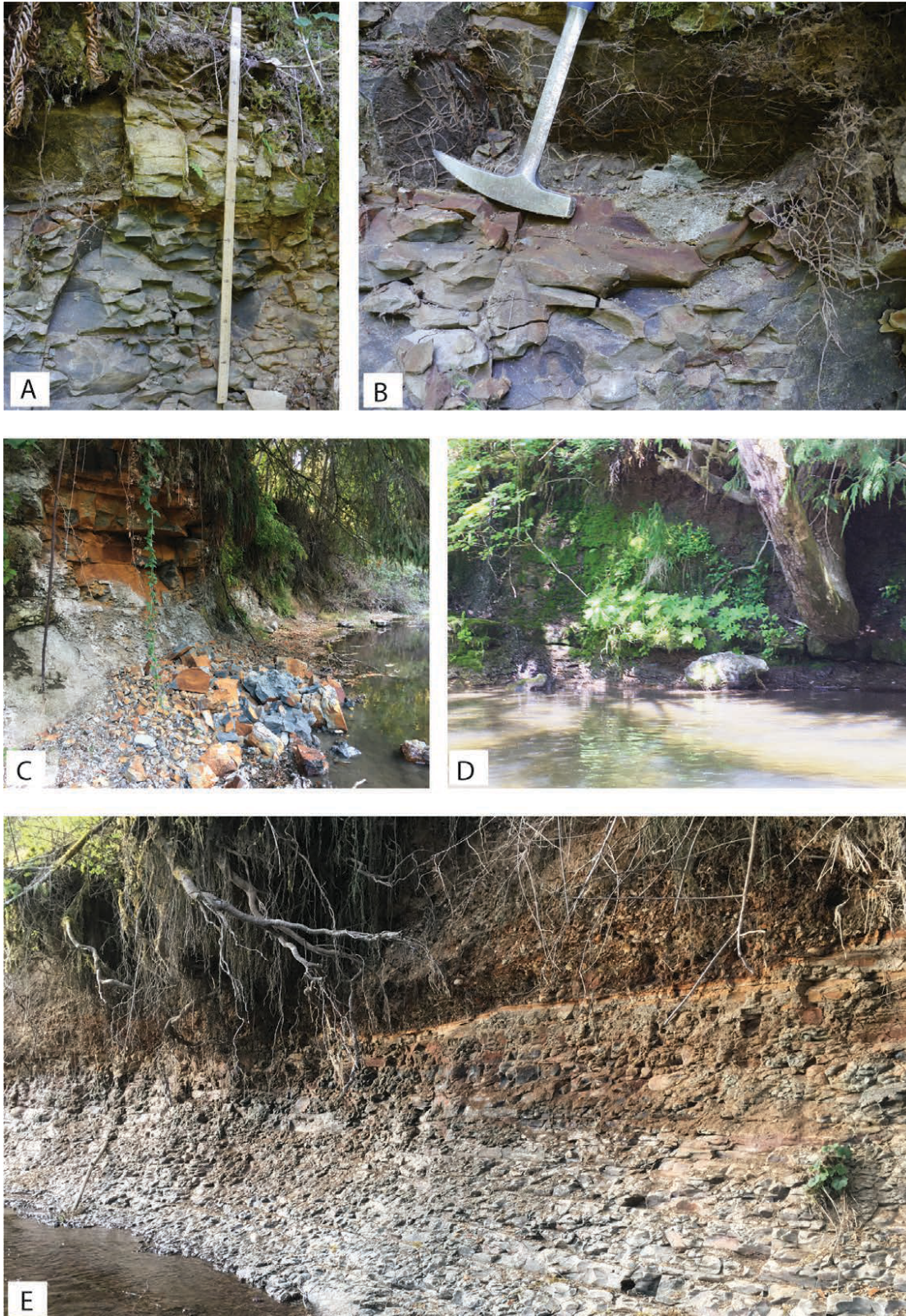
Figure 6. Photographs of exposures. A. Upper turbidite bed with meter-stick for scale. Note sharp base of bed. B. Closeup of the base of the upper turbidite bed showing scour channel filled with medium sand. C. Rockfall in predominantly medium- to thick-bedded mudstones 1-3 meters below lower turbidite bed. Blocks in background are pieces of turbidite bed fallen from the bank. D. Lower turbidite bed at a point where it descends to near river level. E. Medium-bedded mudstones at base of stratigraphic section. Upper part of bank exposure is composed of Pleistocene fluvial gravels.

Echinophoria (now *Liracassis*) *dalli* and *Echinophoria* (now *Liracassis) fax* zones were described from the Lincoln Creek Formation, southwestern Washington (Armentrout 1975, 1981). Range extensions of all three nominal taxa since the publication of this chronology (data from the University of California Museum of Paleontology [UCMP] and University of Washington Burke Museum [UWBM]) have limited the reliability for the biozonal scheme. Faunal assemblages of marine invertebrates are more characteristic of depositional setting than sequential ages and, in particular, methane seep assemblages are recognized by characteristic taxa from late Eocene through the Oligocene-Miocene boundary (Hickman 1976, Hickman 1984, Nesbitt 2018). However, one species that occurs throughout the studied Rock Creek section of the Keasey Formation, *Anechinocardium weaveri* (Anderson and Martin, 1914) is chronologically diagnostic and restricted to the middle member of the Keasey Formation (Hickman 2015). *Bathybembix columbiana* (Dall, 1909) is restricted to the lower member of the formation, therefore defining the subjacent biozone.

Vertebrae of a basilosaurid cetacean were collected just west of the Rock Creek carbonate seeps, within the middle member of the Keasey Formation (Uhen and
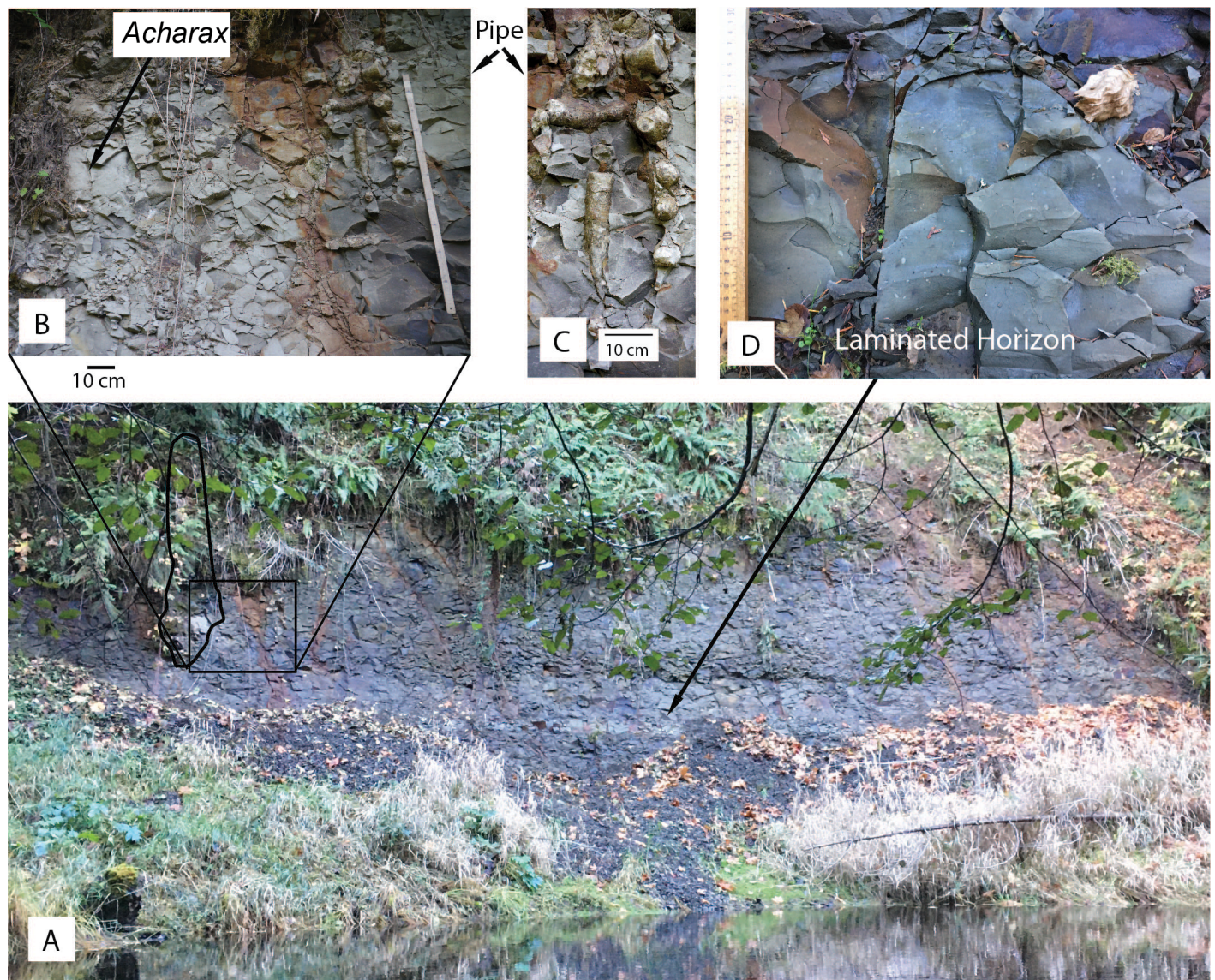
Figure 7. The Second Seep Site. **A.** The exposure is composed of medium to very thick-bedded "massive" mudstone with the seep at its east side. The limestone column is 0.40-0.70 m wide and 3 m high and is outlined. **B.** *Acharax dalli* (Clark, 1925) Auctt. is on the western periphery of the column. Additional smaller vertical and horizontal pipes including stacked concretions occur to the west one meter. **C.** Detail of smaller pipes and stacked concretion. D. Faintly laminated siltstone with sporadic tubular traces.

Taylor 2020). Notably this is the first well-documented record of a basilosaurid from the northeastern Pacific. The Keasey Formation has not yielded abundant vertebrate fossils but those that have been collected include bony fish throughout as well as a new genus of basking shark *Keasius taylori* Welton, 2013 and the flightless marine bird *Phocavis maritimus* Goedert, 1988, from the upper part of the middle member. The whale specimen certainly indicates no later than Priabonian (Late Eocene) while the others are also consistent with the above ages attributed to the Keasey Formation above.

ROCK CREEK SECTION AND SEEP CARBONATES

This Rock Creek study yielded three seep sites, termed Main, Second and Third in descending size. A measured stratigraphic section of the Main Seep Site and adjacent areas with collecting localities is presented in Figure 2. The limestone lithosome of the Main seep is 7 m high and 10 m wide (Figs. 3, 4, 5). The west side is poorly exposed and future erosion could expose a more extensive carbonate body. Lithology of the strata laterally adjacent to the limestone is characteristic of the middle member of the Keasey Formation. The measured section, from about 25 m below to a few meters above the seep carbonate, reveals predominantly medium to very thick-bedded, highly tuffaceous and heavily-bioturbated light gray siltstone (Figs. 2, 5). The sequence includes two turbidite beds with abundant pumice fragments (Figs. 2, 6A, 6B, 6D). They have sharp basal contacts with sand-size detritus at the base that grades upward to silt-size debris. Contacts between the non-turbidite beds characteristically are diffuse, although sharp parting planes are common in the lower 9 m of the stratigraphic section.

Within the measured section, most of the siltstone beds are massive in appearance, although the lithology is mottled as a result of bioturbation and locally preserves relic lamination. Burrows most commonly are 1-2 mm in diameter. One bed, at the Second Seep Site, is notable in being sparsely bioturbated and preserves weak and predominantly low-angle cross lamination (Fig. 7D). The basal several meters of the stratigraphic section are medium-bedded (Fig. 6E) and faintly laminated. The strata contain numerous horizons with subspherical concretions ranging in diameter from a few to 10 cm. Oblate calcareous concretions up to a meter in diameter occur in some beds.

The Main Seep Site is a carbonate body that exhibits a complex arrangement of dense limestone intermixed with irregular (blebby) concretions set in a mudstone matrix (Figs. 3A, 4). The limestones commonly preserve large articulated bivalves, *Conchocele taylori* Hickman 2015 (Figs. 2, 4, 8A, 8B) in places in profusion, but with an admixture of single valves and shell fragments.

Another commonly associated bivalve, *Acharax dalli* (Clark, 1925) Auctt., occurs primarily in the periphery of the limestone body (Figs. 4). Below the Primary Seep site are 1-2 meters of black mudstone with small blebby nodules which yields seep-specialized species including common *Acharax dalli* and rare *Conchocele taylori*.

The Second Seep Site is situated 75 m west of the Main Site (Fig. 1) and is approximately coeval with it. The Second Seep includes a limestone column, 40 to 70 cm wide and approximately 3 m in height within the mudstone strata. While there is a definite base to the limestone mass, as it is underlain by mudstone, its upper part is eroded. The limestone column is composed of an association of amalgamated bulbous, dense concretions. It was not determined whether there are any tubular pipe-like vents within it. The easterly vertical contact with mudstone is sharp. In contrast the western edge contains isolated and irregularly shaped limestone concretions within the mudstone. *Acharax dalli* occurs infrequently in the periphery of the limestone column and the immediately adjacent mudstone. No macrofauna were observed well within the Second Seep Site lithosome.

One meter to the west of this limestone column are two vertical carbonate pipes and some associated horizontal concretions (Fig. 7C). These carbonate features appear to be homogenous internally and do not preserve any associated macrofauna. The most westerly of the two pipes preserve a series of vertically stacked subspherical concretions. The pipe is comparable to putative macrofaunal burrow conduits described elsewhere (e.g., Campbell et al. 2008, Wiese et al. 2015, Blouet et al. 2021) that focused methane seepage in mudstones, and the Rock Creek concretions appear to have formed within inferred burrows.

The Third Seep Site, about 55 m west of the Second Seep, consists of small blebby carbonate concretions averaging 5-15 cm across within mudstones (Fig. 5). These do not appear to preserve any macrofauna.

Except for the thyasirid bivalve masses at the Main Seep Site (Fig. 8A, 8B, 8E), large bivalve shells (substantially greater than 1 cm across) are few and widely scattered. Molluscan shells and fragments, consisting primarily of pelecypods but including a few gastropods, less than 1 cm across are common and widespread. These may occur in concentrations several centimeters across and typically are bioturbated with the shells often in random orientations. Small-scale concentrations of

size-sorted foraminifera were also noted. Scaphopods, of the genus *Fissidentalium* P. Fischer, 1885, occur only sparingly throughout most of the measured 35 m stratigraphic section. This scaphopod is notably common, however, in the black mudstone beneath the limestone at the Main Seep Site (Fig. 5, UCMP locality IP16631) and in the mudstones laterally adjacent to the Second Seep Site (Fig. 5).

STABLE ISOTOPES OF ROCK CREEK CARBONATES

Stable carbon and oxygen isotope ratios obtained from samples of the carbonate body and from benthic foraminifer at the Primary Seep Site are presented in Table 2.

Results of carbonate rock analyses

Shells range from articulated and entire to scattered and fragmental (Fig. 8). Most of the microcrystalline carbonate samples yielded $\delta^{13}C$ values from -30.37 to -48.47‰ PDB, and exhibited $\delta^{18}O$ values from -4.57 to -9.55‰ PDB. The former is indicative of anaerobic oxidation of methane (AOM) in shallow seafloor sediments and the latter likely reflect late-stage burial diagenesis (cf. Campbell 2006 and references therein). Four samples returned isotopic values outside of these ranges.

Sample RC9 (Fig. 8C) displayed a homogeneous rather than nodular microcrystalline carbonate texture. Its positive $\delta^{13}C$ (+5.44‰ PDB) and $\delta^{18}O$ (+3.81‰ PDB) signatures are unusual, with the carbonate carbon value suggestive of a porewater dissolved inorganic carbon pool affected by methanogenesis, which usually occurs deeper in the sediment column than the AOM induced carbonate (above) that forms at seafloor seep sites. The inferred deeper formation depth of RC9)- could be supported by mineralogic information through the presence of dolomite, a carbonate mineral that may be formed at depth at seep sites, with the typically smooth slabs later exhumed at the seafloor by current winnowing and erosion (cf. Campbell et al. 2010). The positive $\delta^{18}O$ value of RC9 may be related to gas hydrate dissociation or could be explained by fractionation of oxygen isotopes during dolomite formation, or by ^{18}O-enrichment during smectite to illite transformation (Greinert et al. 2001, Campbell 2006). The latter occurs during burial diagenesis, and isotopic heterogeneities resulting from such clay mineral alteration are more likely to be preserved in ancient seep limestones than gas hydrate dissociation, which may be modified during diagenesis (J. Peckmann, pers. comm. 2022).

The second isotopically unusual carbonate sample is RC10A, an irregular, coalesced nodular, medium to dark

Table 2. Isotope data from sediment samples and foraminifera. Foraminiferal samples are *Globobulimina auriculata*, *G. pacifica*, or *Uvigerina cocoaensis*.

Carbonate sediment sample	Foraminifera taxon	$\delta^{13}C$ % PDB	$\delta^{18}O$ % PDB
RC9		5.44	3.81
RC10A		-45.18	12.85
RC10B		-30.37	-8.83
RC11		-40.25	-4.57
RC20		-13.08	-10.48
RC21		-54.66	-0.92
RC22		-43.41	-8.31
RC23		-48.47	-8.41
RC24		-45.38	-9.55
RC25B		-42.33	-8.94
RC26		-41.76	-8.56
RC27		-43.28	-9.04
WS1		-43.33	-7.18
WS2		-44.80	-6.66
WS3A		-46.96	-9.05
WS3B		-41.37	-6.51
W4		-52.48	-4.99
	G. auriculata	-2.6	-2.8
	G. auriculata	-17.7	0.6
	G. auriculata	-5.8	-0.1
	G. auriculata	-40.6	0.3
	G. auriculata	-9.7	0.8
	G. pacifica	-34.9	-1.5
	G. pacifica	-46.0	0.7
	G. pacifica	-45.9	0.3
	G. pacifica	-4.4	-2.7
	U. cocoaensis	0.2	0.4
	U. cocoaensis	0.6	0.3
	U. cocoaensis	0.3	0.4
	U. cocoaensis	0.3	0.4
	U. cocoaensis	-0.3	0.5
	U. cocoaensis	-30.9	0.3
	U. cocoaensis	-4.1	0.3
	U. cocoaensis	0.4	0.5
	U. cocoaensis	-1.2	0.5
	U. cocoaensis	0.6	0.4
	U. cocoaensis	-0.7	0.2
	U. cocoaensis	0.1	0.3
	U. cocoaensis	-0.7	0.0
	U. cocoaensis	0.0	0.3
	U. cocoaensis	-12.6	0.3
	U. cocoaensis	-1.4	-1.6
	U. cocoaensis	0.0	-1.1
	U. cocoaensis	-0.1	0.2
	U. cocoaensis	0.0	0.3
	U. cocoaensis	-5.1	0.2
	U. cocoaensis	-5.1	0.0
	U. cocoaensis	-0.4	0.7
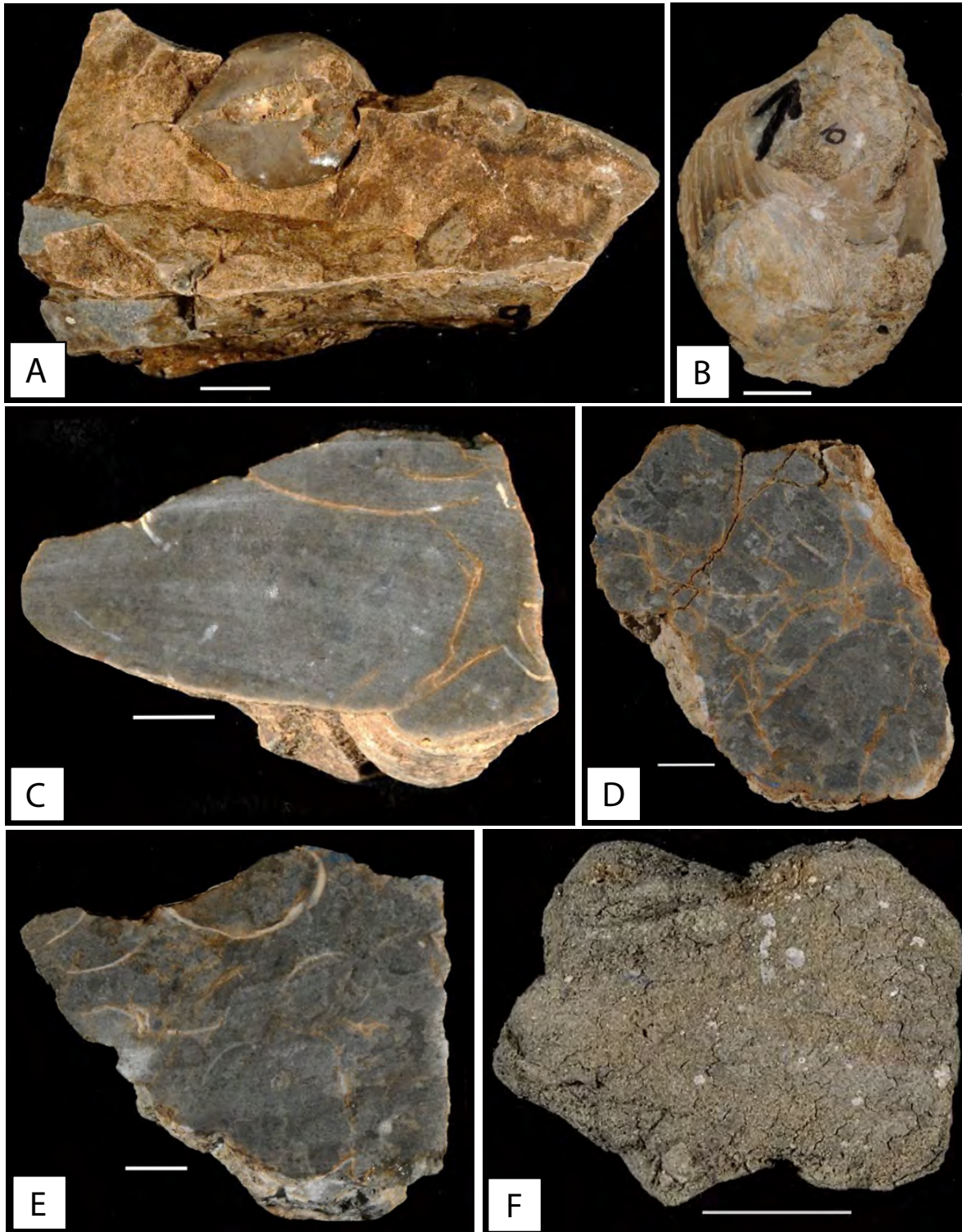
Figure 8. Select carbonate rock hand samples from the Main Seep Site, with some showing taphonomy of macrofossil occurrences. **A.** Articulated specimens of *Conchocele taylori* Hickman, 2015 on weathered (orange-brown stained) outer surface of medium gray colored microcrystalline carbonate; sample RC9(2). **B.** Articulated specimen of *C. taylori* with partial recrystallized shell, found in stratigraphic up position, and infilled with medium gray microcrystalline carbonate sample RC10B. **C.** Dark gray, homogeneous to slightly mottled microcrystalline carbonate with scattered, thin-shelled bivalve fragments; sample RC9. **D.** Irregular, coalesced nodular, medium to dark gray microcrystalline carbonate with scattered, straight bivalve shell fragments; sample RC10A. **E.** Irregularly nodular and mottled microcrystalline carbonate to cemented breccia of medium to dark gray microcrystalline carbonate with scattered, relatively thick, single curved valves of *C. taylori* shells; sample RC11. **F.** microcrystalline carbonate cemented, friable calcareous sandstone with nacreous molluscan shell fragments; sample RC21.

gray microcrystalline carbonate with scattered bivalve shell fragments (Fig. 8D) that exhibits a typical AOM $\delta^{13}C$ value of -45.18‰ PDB and a strongly ^{18}O-enriched signature of +12.85‰ PDB. Smectite diagenesis during burial is also suggested, which could be confirmed by more detailed mineralogical assessment of the sample.

A third isotopically distinctive carbonate sample, RC20, is a weathered, iron-stained, dark gray cemented nodular microcrystalline carbonate with a $\delta^{13}C$ value of -13.08 ‰ PDB and the most depleted $\delta^{18}O$ value of the measured samples (-10.48‰ PDB). The carbonate carbon signature appears diluted by seawater and the $\delta^{18}O$ depletion signals burial diagenetic alteration of the carbonate sample.

The final outlier in stable carbon and oxygen isotopic signatures of the studied rocks (Table 2) is RC21, a friable, fine-grained sandstone containing diminuted shell hash cemented by microspar (Fig. 6F). It yields the most C-13 depleted measurement in this study of -54.66 ‰ PDB, and a $\delta^{18}O$ value (-0.92‰ PDB) close to that of seawater. It is common for strongly depleted carbonate carbon samples at seep sites to also be enriched in O-18 relative to other samples (e.g., Campbell et al. 2002, 2008, 2010, Campbell, 2006). Methane-charged fluid flow through porous sandy horizons was likely more advective than through mudstone, potentially driven by sustained microbial AOM (e.g., Greinert et al. 2001, Campbell et al. 2010). Further study of additional samples and their mineralogic assessment would help verify the above interpretations of the origin of the Rock Creek seep limestones.

Results of foraminiferal carbonate analyses

The foraminiferal data listed in Table 1 were included in comparative studies of seep signatures in benthic foraminiferal tests from four rock units of the Cascadia forearc (Martin et al. 2007, Nesbitt et al. 2013). Foraminiferal taxa used in this study were *Globobulimina auriculata* (Bailey, 1851), *G. pacifica* Cushman, 1927 and *Uvigerina cocoaensis* Cushman, 1925. These species were chosen because they were most numerous in the fossil seeps, and they, or their closely-related species, are frequently found in modern seeps (Bernhard et al. 2001, Rathburn et al. 2003, Martin et al. 2010).

Of note in the foraminiferal carbonates is the degree of reduction and variability in ^{13}C values, which were considerably more variable than the 0.2 to 0.4‰ PDB expected in ambient sea water (Rathburn et al. 2003). In *Globobulimina auriculata*, $\delta^{13}C$ = -38‰, *G. pacifica* displayed $\delta^{13}C$ = -41.6‰, and in *Uvigerina cocoaensis*,

$\delta^{13}C$ = -40.5‰. This variability of ^{13}C values, both within and across species, is recorded widely in modern and ancient seep settings. (e.g., Rathburn 2003, Martin et al. 2007, 2010, Panieri et al. 2009, Burkett et al. 2018). Of interest, however, is the clear distinction in $\delta^{13}C$ values between the two species sampled. While both are infaunal, *Globobulimina* is a deep infaunal genus, and *Uvigerina* is a shallow infaunal form, though this is a matter of millimeters or centimeters (Gooday et al. 2008, and references therein). The relationship between foraminifera and their environments (and microenvironments) is complex and not clearly understood; nonetheless, the individuals may be reflecting environmental differences such as fluid micro-passages or bioturbation which vary at different depths in the sediment. Oxygen isotopes, however, displayed much less variation, with $\delta^{18}O$ values ranging between -2.8 and 0.8‰ PDB. This combined with $\delta^{13}C$ values ranging between -30‰ and -50‰ suggests derivation from AOM of thermogenic methane in the shallow seafloor (Claypool 1974).

MOLLUSCAN PALEONTOLOGY

The molluscan fauna reported here was collected over a linear map distance of about 600 m extending from approximately 500 m west to 90 m east of the Main Seep limestone outcrop and over a streambed distance of approximately 2000 m (Fig. 9). Significant faunal assemblages from stream-bank outcrops are shown on a measured vertical stratigraphic section of approximately 35 m (Fig. 10). There is considerable taphonomic alteration of the molluscan specimens attributable to diagenesis and modern exposure in stream-bank outcrops that are seasonally submerged. However, remnant original shell material and detail on internal and external molds are sufficient to recognize recurring mollusk associations or communities previously defined from many localities in the Keasey Formation (Hickman 1984). The Rock Creek seep fauna is notable in its depauperate, species-dominant mollusk fauna. It is the type locality of the chemosymbiotic thyasirid bivalve *Conchocele taylori* Hickman, 2015. This species is abundant in the seep limestone facies, including dense concentrations of double-valved individuals. The chemosymbiotic solemyid bivalve *Acharax dalli* (Clark, 1925) Auctt. occurs in the coeval siltstone underlying and immediately adjacent to the carbonate facies (Nesbitt et al. 2006).

Taxonomic accounts, specimen illustration, and stratigraphic ranges within the limited outcrop extent of the Rock Creek methane seep section are not relevant to Keasey Formation biostratigraphy, age and correlation.

However new collections bracketing the seep limestone outcrop substantially increase the diversity of the molluscan fauna originally reported at the Main Seep Site (UCMP Locality IP16005) by Nesbitt et al. (2006) and Hickman (2015). Although most of the genera and species are necessarily treated in open nomenclature due to poor preservation and lack of diagnostic characters, family-groups are readily identified and distinctive life habits, trophic adaptations, and physiological capabilities

Table 3. List of mollusk species from the Keasey Rock Creek cold seep section.

Bivalves
    Protobranchs
        Acharax dalli (Clark, 1925) Auctt.
        Acila sp. cf. *A. minima* Hickman, 1969
        Nuculana washingtonensis (Weaver, 1916)
        Propeleda? sp. indet.
        Nuculanidae gen. et sp. indet. a
        Nuculanidae gen. et sp. indet. b
        Portlandia chehalisensis (Arnold, 1908)
        Yoldiidae gen. et spp. indet.
    Pteriomorphs
        Delectopecten keaseyorum Hickman, 2023
    Heteroconchs
        Conchocele taylori Hickman, 2015
        ?Conchcocele bathyaulax Hickman, 2015
        ?*Moerella quasimacoma* Hickman, 2015
        Anechinocardium weaveri (Anderson and Martin, 1914)
        ?*Lamelliconcha clarki* (Dickerson, 1917)

Gastropods
    Architaenioglossids
        Epitonium (Boreoscala) condoni (Dall, 1908)
        Naticidae gen. et spp. indet.
    Neogastropods
        Exilia bentsonae Hickman, 1980
        Procerapex bentsonae (Durham, 1944)
        Turridae gen. et sp. indet. a
        Turridae gen. et sp. indet. b
        Turridae gen. et sp. indet. c
        Bonellitia? sp.
    Opisthobranchs
        Scaphander impunctatus Hickman, 1980

Scaphopods
        Fissidentalium cf. *F. laneensis* Hickman, 1969
   *Cadulus* n. sp.

provide useful insights into life in extreme geochemical settings in and adjacent to hydrocarbon seeps. For this reason, a species list is presented in Table 3.

Hickman (2015) reviewed occurrences of seep carbonates and seep-associated faunas at two additional sites in the Keasey Formation, which occur within 25 km of one another: Vernonia-Timber (Campbell and Bottjer 1993) and the crinoid lagerstätte at Mist (Burns et al. 2005). Together these three localities illustrate different points on a continuum from effusive to diffusive expulsion of methane seepage at the seafloor, chemosynthetic activity, and biological opportunism in geochemically challenging environments. Some additional fossil taxa of the upper member of the Keasey Formation are related to living taxa now known as members of cold seep communities. These include a giant limid bivalve (Järnegren et al. 2005) and hexactinellid sponges (e.g., Campbell et al. 2010, Kuechler et al. 2011). Although there are no known seep carbonates or effusive seeps in the upper member, the Keasey *Acesta* Association (Hickman 1984) includes a relict terebratulid brachiopod and a basal arcoid bivalve, extending a well-documented earlier cold seep history of basal arcoids in late Mesozoic active margin sediments in California (Hickman 2021). The first occurrence of a giant limid on the Cascadia Margin is in the early late Eocene Nestucca Formation along with a relict Mesozoic gastropod, predating Keasey deposition but coinciding with the onset of subduction and arc volcanism and partially resting on basalt crust of the accreted volcanic province of Siletzia (Hickman 2018).

Recurring paleo-assemblages at the Keasey study site include the following taxon associations: a chemosymbiotic Thyasirid-Solemyid Association, a deposit-feeding infaunal Protobranch Scaphopod Association, a free-living epifaunal carnivorous Turrid-Naticid-Epitoniid gastropod Association, an epifaunal Mud Pecten Association, and a low-diversity shallow infaunal association of siphonate, suspension-feeding bivalves. New collections bracketing the seep limestone outcrop substantially increase the diversity of the depauperate molluscan fauna originally reported at the Main Seep Site (localities UCMP IP16005, and UWBM B7272) by Hickman (2015) and Nesbitt et al. (2006). A summary and characterization of these molluscan associations at the Rock Creek site is presented below.

Molluscan Associations

Thyasirid-Solemyid Association— The carbonate limestone precipitated at the site of methane seepage enveloped densely packed specimens of the thyasirid
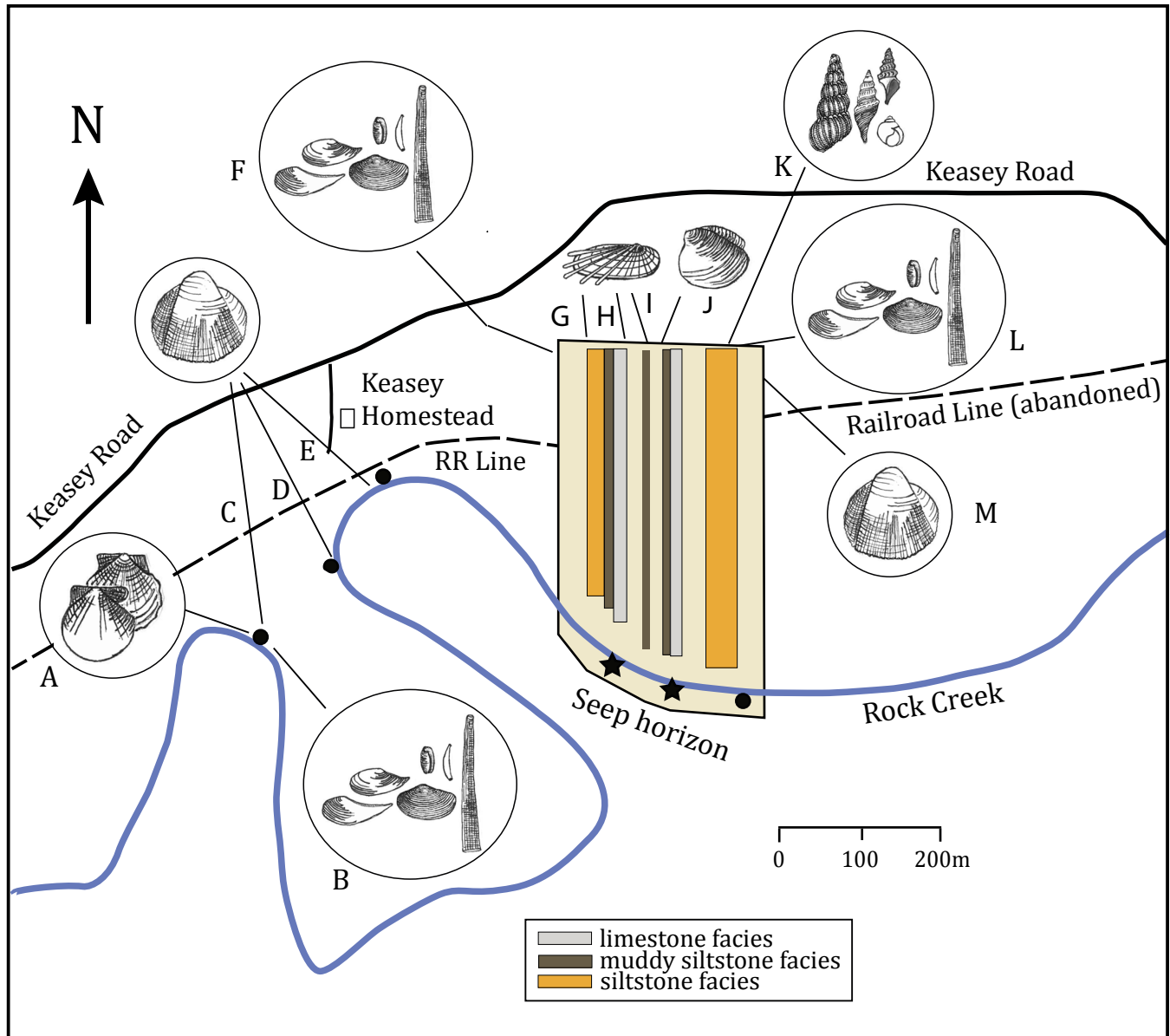
Figure 9. Map occurrences of major macrofaunal elements and associations at the cold seep horizon in limestone, muddy siltstone, and siltstone facies and exemplar outcrops of non-chemosymbiotic. A. byssally attached bivalves from the Mud Pecten Association; C, D, E, M. Suspension-feeding heterodont bivalve association; B, F, L, deposit-feeding Protobranch Association; G, H I, J, chemosymbiotic Thyasirid-Solemyid Association; K. Turrid–Naticid–Epitoniid Association.

Conchocele taylori Hickman, 2015 in life position. At Rock Creek, *C. taylori* has not been collected outside of the effusive seep limestone facies of the type locality (Main Seep Site), except for one articulated specimen from the immediately subjacent siltstone. Although endemic to the Rock Creek type locality at the time of description, this species is now recognized from six Paleogene seep carbonate sites in western Washington (Hryniewicz et al. 2017, UWBM unpublished data) where it had been lumped previously under *C. bisecta* Conrad, 1849. A

second *Conchocele* species, also lumped under Conrad's name, *Conchocele bathyaulax* Hickman, 2015, was described from the Timber-Vernonia seep in the lower member of the Keasey Formation. This species also is now recognized from five Paleogene seeps in western Washington (Hryniewicz et al. 2017, UWBM unpublished data). Broad application of Conrad's name undoubtedly masks the diversity in a temporally long-ranging and geographically widespread species complex (Hickman 2015). In addition to anatomical and behavioral
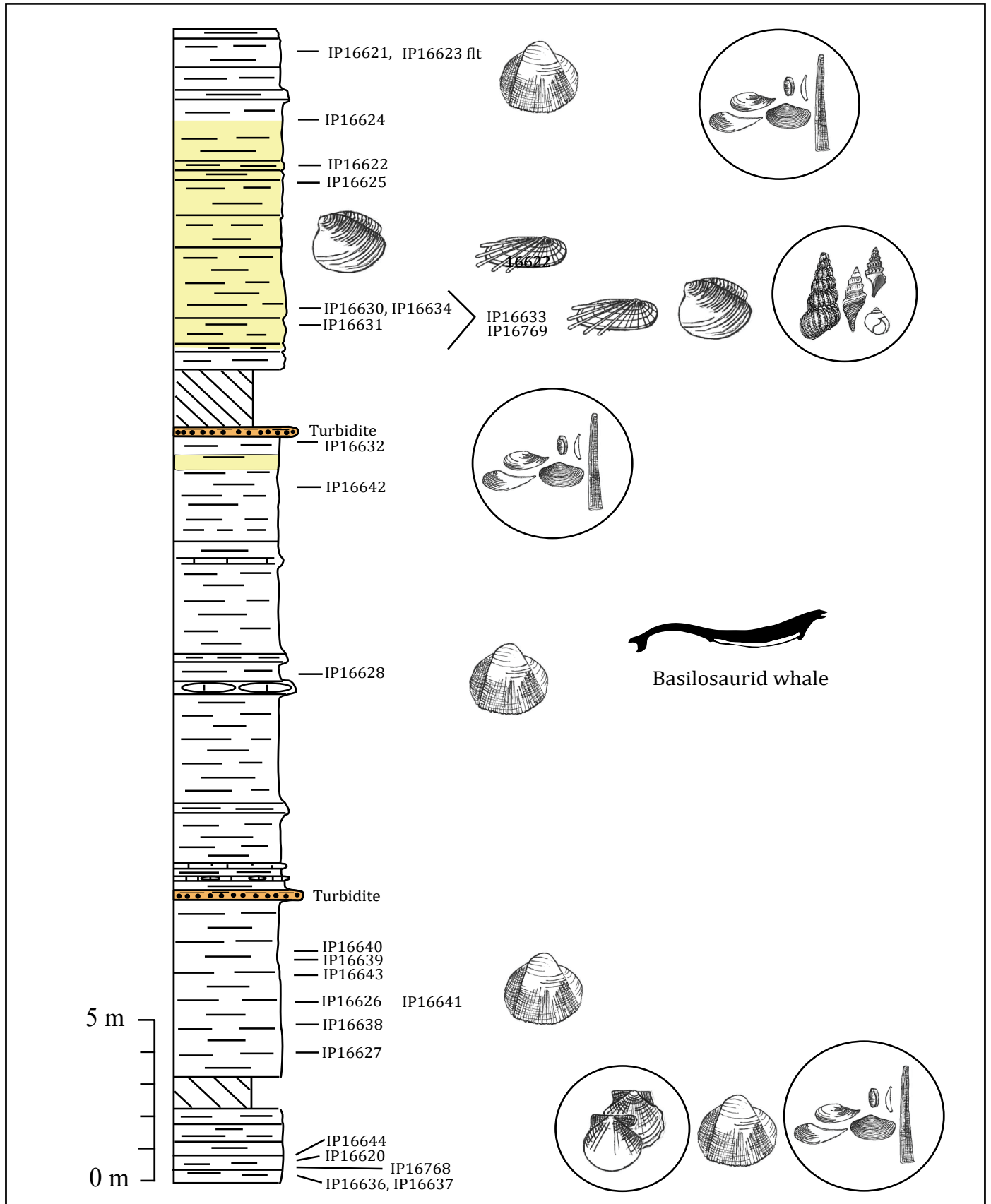
Figure 10. Stratigraphic distribution of macrofaunal elements and associations.

documentation of sulfide mining by a superextensible foot in chemosymbiotic thyasirids (Dufour and Felbeck 2003), detailed three-dimensional microanatomical studies have revealed extreme modification of the gill into a tubular meshwork in which specialized cells lining tubes provide intracellular housing of the chemosynthetic bacteria (Oliver 2014).

A single, poorly-preserved larger, more strongly-inflated bivalve in the Rock Creek siltstone facies outside the seep may represent *Conchocele bathyaulax*, extending its range in the Keasey Formation into the lower part of the middle member. A similar large-shelled thyasirid, treated in open nomenclature as *C. bathyaulax*, has been reported from two Paleogene seeps in Washington (Hryniewicz et al. 2017).

Thyasirid bivalves are not restricted to effusive seeps and sites of carbonate precipitation. They are, however, well-known as oxygen minimum zone bivalves that can tolerate severely hypoxic conditions and thereby take advantage of high microbial chemosynthetic productivity under reducing conditions (e.g., Oliver and Levin 2006). The solemyid bivalve *Acharax dalli* (Clark, 1925) Auctt. occurs at the Main Seep Site mostly in the coeval muddy siltstone facies as well as in the Second Seep Site in muddy siltstone and limestone adjacent to and in the periphery of the three-meter-high conduit. As with the thyasirids, the assignment of all Cascadia Margin solemyids to a single genus and species, *Acharax dalli*, likely masks hidden diversity in the fossil record.

Solemyid bivalves (*Solemya* s.s., *Acharax*, and *Petrasma*) are of primary importance to understanding the paleoenvironment of the Rock Creek seep because their Y-shaped burrow systems (Fig. 11) must span oxic-anoxic interfaces. This is required in order to supply their bacterial symbionts with both reduced compounds and oxygen, and well as to meet their own oxygen needs. They are non-siphonate, and the clam lives at the triple junction of the Y created and maintained by the foot. Fluids charged with sulfide or methane also provide the energy substrate for fixing carbon in living thyasirid and lucinid bivalves (Hickman, 1984, 2003b). As gutless, deeply buried, infaunal bivalves they are entirely dependent on chemosymbiotic bacteria for nutrition (Distel 1998, Stewart and Cavanaugh 2006). They also are the oldest chemosymbiotic bivalves, with a fossil record dating from the Early Ordovician (Cope, 1996). Solemyid specimens are so poorly preserved in the Keasey Formation that they have been overlooked or not collected previously. However, we have found solemyids to be second in abundance to *C. taylori* in the Rock Creek section and

seep-associated fauna. Specimens occur principally in the dark gray mudstone facies that is spatially associated with the limestone facies. This distribution of *Acharax* at Rock Creek is consistent with reports of the genus in a peripheral zone at both modern and ancient seeps (Sahling et al. 2002, Nesbitt & Campbell 2004, Jenkins et al, 2007).

Figure 12 illustrates chalky remnant material on an articulated internal mold (Fig. 12A) and small fragments of extraordinarily thin shells (Fig. 12B) that are inadequate for assignment to genus group or species. All fossil solemyids from the Cascadia Margin are currently assigned to *Acharax* Dall, 1908 (e.g., Goedert and Squires 1990, Goedert et al. 2003, Nesbitt et al. 2013), and revision of available names, type material, and specimens in museum collections is beyond the scope of this
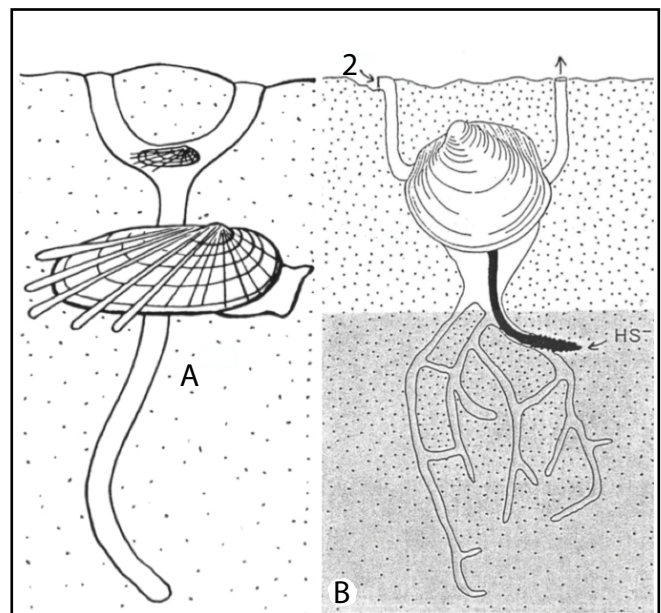
Figure 11. Depiction of solemyid burrow (Fig. 11A, from Hickman 1984) and lucinid burrow (Fig. 11B, from Hickman 1994, 2003b). Such burrows span oxic-anoxic boundaries to provide their symbionts with sulfide from the sediment and oxygen from the water column and as well as meeting their own oxygen needs. The presence of an articulated fossil solemyid in life position (i.e. in situ) indicates the presence of an ancient oxic-anoxic interface, regardless of whether the burrow is clearly preserved. Extensive bioturbation characteristic of the massive Keasey siltstone and mudstone units is likely to obliterate uncemented burrow ichnofabrics of solemyids. See Droser & Bottjer (1989) for history of bioturbation. On the other hand, burrows of decapods are more likely to be preserved since decapod crustaceans secrete a calcareous cement that prevents burrows from caving — e.g. collophanite (an amorphous calcium phosphate). See Weimer and Hoyt (1964).
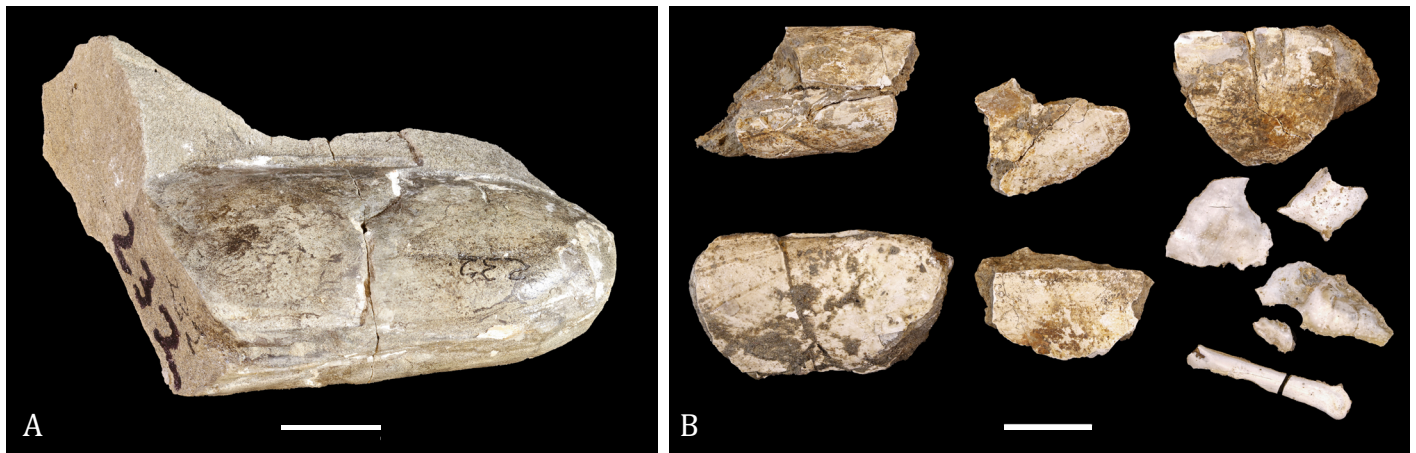
Figure 12. Solemyid bivalve preservation in the seep mudstone facies. **A.** Chalky remnant shell material on an articulated internal mold collected in life orientation. **B.** Fragments of chalky articulated internal molds and extremely thin shell fragments that exfoliated during collection. Scale bars = 1 cm.

paper. However, it is important to note that both *Acharax* and *Solemya* Dall, 1908, as diagnosed by features of the condrophore and ligament (Taylor et al. 2008), occur in the Keasey Formation (Hickman, personal observation).

Protobranch Association— New collections from the Rock Creek section include relatively diverse assemblages of small-shelled, deposit-feeding protobranch bivalves (nuculanids, yoldiids, and a nuculid) with two scaphopods (a large dentaliid and a minute siphonodentaliid). This association is recognized at 12 localities between the base and top of the measured section. The abundance of deposit feeders and absence of suspension feeders is consistent both with elevated productivity of free-living chemosynthetic microbes on the margins of seepage areas, and the ability of many living protobranch bivalves to tolerate and detoxify sulfide and to obtain and store oxygen in dysoxic environments (Hickman 2023).

The scaphopods, species of *Fissidentalium* P. Fischer 1885 and *Cadulus* Philippi, 1844, in this faunal association are interesting as members of a foraminiferivorous (*sensu* Hickman and Lipps 1983) class of mollusks. Feeding selectively on foraminiferans, scaphopods have specialized tentacles that recognize and capture their prey and buccal pouches in which the food species are stored prior to mastication by the radula. For a review and references see Gudmundsson et al. (2003). The presence of scaphopods throughout the Rock Creek section coincides with our recovery of large foraminiferal populations at several localities.

An additional species of interest in this association is a small cephalaspidian gastropod of the genus *Scaphander* Montfort, 1810. Collectively known as bubble shells, cephalaspidians form a well-supported clade of marine gastropod families noted for anatomical specialization of the alimentary system for carnivory (Mikkelsen 2002). Eilersten and Malaquias (2013) provide rigorous documentation of foraminiferans in the gut contents of seven living deep-water species of *Scaphander*. The Keasey scaphandrid occurs in all three members of the formation (Hickman 1980) and is a distinctive element of the Rock Creek Protobranch Association.

Scaphander further reinforces the link between the Rock Creek protobranch assemblages and other Paleogene hydrocarbon seeps on the Cascadia Margin. Scaphandrids are recorded along with protobranchs in the Paleogene Whiskey Creek, Satsop River, and Canyon River seep faunas in western Washington in association with chemosymbiotic solemyid, thyasirid, and vesicomyid bivalves (Peckmann et al. 2002, Goedert et al. 2003).

Turrid–Naticid–Epitoniid Association—The Keasey Formation contains a diverse fauna of small-shelled vermivorous turrid gastropods (Hickman 1976, 1980, 1984), typically co-occurring with one or more shell-drilling predatory naticids and less often with shells of large parasitic epitoniids, presumably with an unknown soft-bodied anthozoan host. These taxa are all poorly preserved, but elements of the association were recovered at six localities in siltstone facies, including a locality stratigraphically equivalent to the main seep site. The turrids at this locality are mineralized internal molds. The only turrid that can be positively identified is *Procerapex bentson*ae (Durham 1944), which is the most common and abundant Keasey turrid, occurring primarily in the middle member of the formation (Hickman 1976). Furthermore, a small gastropod shell preserves

ornamentation suggestive of one of the Keasey species of *Ptychosyrinx* Thiele, 1925.

Mud Pecten Association—Thin-shelled epifaunal pectinid and propeamussiid bivalves occur locally throughout the Keasey Formation, usually in small, discrete clusters. They include both free-living and byssally-attached forms. Collections from two localities near the base of the section include a recently described pectinid species, *Delectopecten keseyorum* Hickman, 2023), that occurs in all three members of the Keasey Formation (Hickman 2023). It was clearly a sessile species, and there are indications at other localities that it formed local colonies in shallow depressions where shell fragments served as sites for byssal attachment. Concentrations of an additional pectinid, *Delectopecten kieli* Hickman, 2023, in the lower member are mixed with numerous fine echinoid spines and fish scales and the clumps may represent fish or elasmobranch regurgitates (Hickman 2023). Different small-shelled pectinid and propeamussiid species occur in the Keasey cold seep fauna at Mist (Hickman 2023) as well as in Paleogene seep carbonates in Washington (e.g., Kiel 2006).

Semi-infaunal and shallow-burrowing heteroconch bivalves—The two most characteristic and abundant bivalves in the Keasey Formation, the cardiid bivalve *Anechinocardium weaveri* (Anderson and Martin, 1914) and the tellinid bivalve *Moerella quasimacoma* Hickman, 2015, occur as isolated specimens as well as in

Figure 13. Early diagenetic infilling of botryoidal aragonite in shell interior of the epitonid gastropod *Boreoscala condoni* (Dall, 1908). Note different size bubbles in successive layers. Scale bar = 1 cm.

other associations. They are shallow burrowing or semi-infaunal siphonate bivalves that are typically articulated and relatively well preserved. The tellinid occurs in all three members, while the cardiid is restricted to the middle Keasey member. *A. weaveri* is noteworthy because it occurs at many localities throughout the Rock Creek section, supporting our assignment of the limestone as well as the whale locality to the middle member. Although it does not occur in life position, *A. weaveri* most commonly is articulated, preserving original shell material and characteristic sculpture. Individuals were therefore not subject to appreciable transport or exposed prior to final burial.

The Keasey Peri-seep Biotope

The Rock Creek section and its distinctive fossil assemblages indicate not only methane seep conditions (chemosymbiotic thyasirid and solemyid bivalves) and traditional background conditions (shallow-burrowing heteroconch bivalves), but also the presence of a formally-designated transitional peri-seep biotope (Hickman (2023, p. 2–3). This biotope includes the protobranch bivalve and mud pecten associations described above and implies diffuse methane seepage.

Shell mineral fills

Paragenetic mineral sequences in the interior voids of gastropod shells and articulated bivalves are another potential source of insight into early diagenetic processes in seep environments. Although most of the gastropods in the seep-associated assemblages in the Rock Creek section lack sufficient shell material for confident species identification, many specimens in the Turrid- Naticid-Epitoniid Association have mineralized internal molds. The successive infill of botryoidal aragonite in the epitoniid, *Boreoscala* Kobelt, 1902 (Fig. 13) suggests a potential for future research on the Rock Creek mollusk associations that occur within and at varying distances from the seep limestones.

Although successive mineralization events in shell fills have not been recognized previously as potential archives of early diagenetic biochemical processes in Cascadia Margin seeps, concentric zoned mineral sequences have been documented in pipes and inferred conduits at seeps in western Washington (Zwicker et al. 2015). From a paleobiological standpoint, the primary interest in the burrows described below is their origin and producers, but they provide similar opportunities for research on the dynamics of methane-rich fluids and gases and the involvement of methanogenic Archaea.

Mollusk-associated sedimentary structures

Sedimentary structures of potential molluscan origin
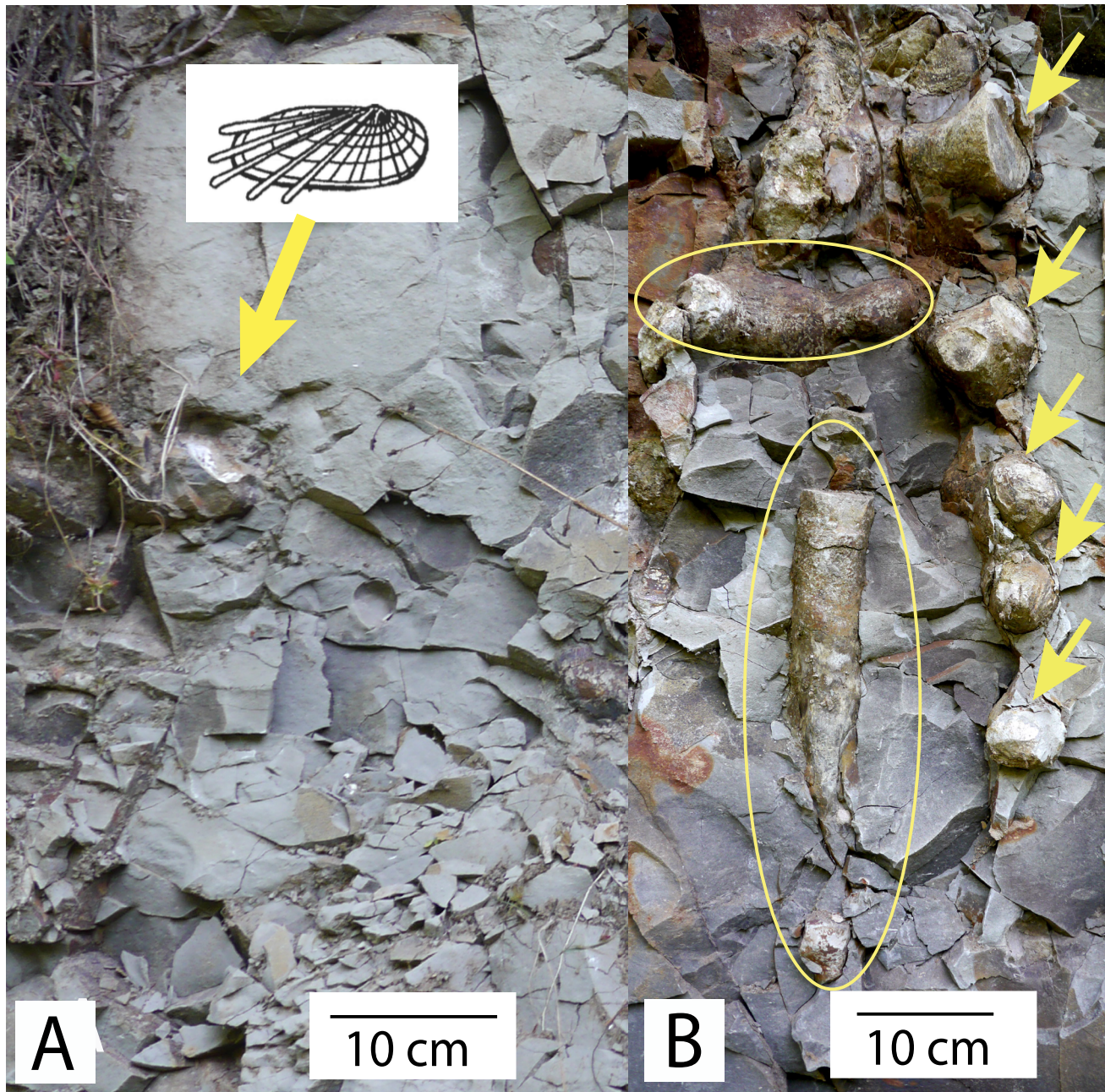
Figure 14. Detail of chimney at the Second Seep Site, where the location of a solemyid bivalve in figure 12A is situated at periphery of seep limestone.

have not been reported previously from the Keasey Formation. At the Second Seep Site an in situ solemyid bivalve (Fig. 14A) occurs adjacent to the 2.5 m high vertical pipe and about one meter from two curious coeval sedimentary structures, a minor vertical pipe and part of a horizontal pipe immediately adjacent to a series of 5 vertically stacked spherical concretions (Fig. 14B). The pipe is comparable to literature illustrations of putative macrofaunal burrow conduits for methane seepage, and the stacked concretions appear to have formed within a

potential burrow conduit. There is a large literature treating fossil seep plumbing structures of metazoan origin, and the Rock Creek section offers future opportunities to contribute to this body of research.

Interest in carbonate chimneys, pipes and columns predates the discovery of chemosynthesis. It also predates recognition that many of these structures originated as metazoan burrows that functioned as conduits for migration of hydrocarbons in the shallow subsurface plumbing of ancient cold seeps. Origin of the

gigantic Eocene limestone columns of the "stone forest" or "upright stones" of Varna on the Bulgarian Black Sea coast has been debated for 200 years (Nachev and Sinnyovsky 2014), with interpretations ranging from ancient temples, sacred sites, petrified forests, coral reefs, or abiotic pathways of fluid migration to more recent detailed evidence of formation by microbially mediated anaerobic oxidation of methane (AOM) (De Boever et al. 2008, Capozzi et al. 2015). Some of the classic localities are tourist attractions and have been preserved as national monuments for public education in the Earth and life sciences. The Bulgarian upright stones have been designated as a UNESCO World Heritage Site.

Ten-meter high and meter-diameter hollow carbonate columns are spectacular, but exceptional. However, smaller tubular pipes also serve as low-resistance pathways for the migration of methane-rich fluids through sediments. At the low-flux diffusive end of the spectrum of fluid migration, metazoan burrows act as conduits at the centimeter scale and are more effective than pressurized pore water in the upper potions of seep migration systems (Zwicker et al. 2015). Cold seep literature has focused increasingly on putative burrow systems of chemosymbiotic macrofauna. For studies of sedimentary structures at cold seeps on the Cascadia Margin, the data range from petrographic sequences of mineral phases in pipes to isotope geochemistry of the carbonate phases and analyses of lipid biomarkers (Peckmann et al. 2002, 2003, 2007; Joseph et al. 2013; Nesbitt et al. 2013, Zwicker et al. 2015). Comparable data from Japan implicate burrows and concretions as evidence for AOM-driven lithification of former hydrocarbon conduits (Miyajima et al. 2018).

The low-diversity thyasirid-dominated Rock Creek sites are perhaps most closely comparable to Late Mesozoic and Early Paleogene seeps, such as a locality in the Arctic Ocean Norwegian island archipelago of Svalbard (Hrynicwicz et al. 2016). As a wood-fall environment, the Svalbard site invites a stretch of speculative comparison with the Rock Creek whale fall (Uhen and Taylor 2020) and as an enriched local source of methane.

Although there is widespread agreement that metazoan burrows are major conduits or pathways for shallow subsurface fluid migration (Wiese et al. 2015) there is considerable remaining debate over whether the burrows were created and occupied by bivalves or by decapod crustaceans (Zwicker et al. 2015). Implication of bivalves has been argued by Campbell (1992), Dufour and Felbeck (2003), and Nobuhara (2003), while crustaceans have been advocated by Peckmann et al (2007),

Wetzel (2013), and Wiese et al. (2015). The presence of both solemyid bivalves and burrowing decapods in the Rock Creek section is therefore ripe for future research (Fig. 11).

For references to >25 papers since 1992 identifying and characterizing carbonate conduit systems see Capozzi et al. (2015). This paper introduces an international workshop volume featuring an additional twelve state-of-the-art research investigations of AOM seep carbonates as pathways of fluid migration.

PALEOBATHYMETRY

Hickman (1974, 1976, 2003a) provided a bathyal depth of deposition for the middle member of the Keasey Formation based on trophic structure of molluscan communities, and the fauna collected from the Rock Creek seep sites confirm this model. Additionally, the benthic foraminifera collected from siltstones in proximity to seep carbonates (KAM 249-251; KAM 239-247) are diverse, prompting McDougall (1979) to give a bathyal depth assignment for that part of the section.

The finely and uniformly textured siltstone lithology is consistent with a bathyal setting, as is the occurrence of turbidite beds. While turbidites may occur in neritic settings (Normandeau et al. 2013, 2015, Warrick et al. 2013), they characteristically are found in deeper water (Covault and Romans 2009, Stow and Smillie, 2020). Current-sorted molluscan shell accumulations are localized and small-scale, indicating at most, weak currents while widespread bioturbation indicates well-oxygenated conditions. Nevertheless, in several beds the presence of primary lamination as well as *Planolites* is consistent with localized dysoxic conditions. Molluscan associations within the seep limestone, mudstone, and muddy siltstone facies indicate a range of oxygenation conditions, including dysoxic and geochemically adverse settings. In summary, deposition of the middle member most likely was in bathyal yet well oxygenated to dysoxic waters.

SUMMARY AND FUTURE DIRECTIONS

The Rock Creek methane seep complex records an early history of the late Eocene onset of arc volcanism on the Cascadia Margin. It also marks the close of the Eocene doubthouse interval of progressive oscillatory global cooling (see Hickman 2021, p. 2-3), the Oi-1establishment of permanent polar icecaps, and the first appearance in the Northeastern Pacific fossil record of low-diversity molluscan seep-related fossil assemblages (Hickman 2023). It provides clear isotopic evidence of

methane-charged fluids in a heterogeneous carbonate lithosome (sensu Wheeler and Mallory 1956). The framework provided here includes the tectonic setting; age and correlation; lithologic description of a variety of seep carbonate structures, coeval mudstone, muddy and sandy siltstone; results of stable isotopic analysis of carbonate rock samples and benthic foraminifera; characterization and interpretation of five distinctive mollusk associations at exemplar outcrops; and paleobathymetric interpretation of the section. The meandering transect of the creek through a relatively small area of shallowly-dipping rock suggests the potential for further exploration of variation and structures within the carbonates and associated mudstone and siltstone. Additional targets of study include paragenetic sequences of gastropod shell fills, biomarker analysis, thin-section and petrographic analysis of pipes and concretions, conduit/pipe morphology and geometry, and characterization of a regional subsurface plumbing system within the lithosome.

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