



Paleocene methane seep and wood-fall marine environments from Spitsbergen, Svalbard

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ARTICLE INFO

Article history:

Received 31 May 2016

Received in revised form 25 August 2016

Accepted 27 August 2016

Available online 30 August 2016

Keywords:

Chemosynthesis-based environments

Conchocele

Ecology

Hydrocarbon seeps

Paleocene

Svalbard

ABSTRACT

Here we describe a Paleocene-aged methane seep locality and an associated layer of sunken wood, from Fossildalen on Spitsbergen, Svalbard, hosted in offshore to prodelta siltstones of the Basilika Formation, Van Mijenfjorden Group. The fossiliferous seep carbonates were first identified in museum collections from expeditions in the 1920s and 1970s, and subsequently sampled as *ex-situ* blocks in the field in 2015. The isotopically light composition ($\delta^{13}\text{C}$ values approaching -50% V-PDB), and characteristic petrographic textures of the carbonates combined with the isotopically light archaeal lipids are consistent with their formation at fossil hydrocarbon seep environment. The invertebrate fauna within the carbonates is of moderate diversity (17 species) and has a shallow water affinity. Wood specimens within the carbonates contain the borings and shells of wood-boring bivalves. The seep fauna is dominated by a species of the thyasirid genus *Conchocele*, common to other seeps of similar age. The data shed new light onto the history of methane seepage on Svalbard, and the evolution and ecology of seep and wood-fall faunas during the latest Cretaceous–earliest Paleogene time interval.

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1. Introduction

Hydrocarbon seeps are sites of submarine hydrocarbon emission, common in shallow to deep marine settings in all oceans (e.g. Hovland, 1992; Fujikura et al., 1999; Domack et al., 2005; Dando, 2010). A high concentration of reduced compounds results in seeps hosting dense communities of invertebrates relying primarily on chemosynthetic primary production, unlike ‘normal’ marine benthic faunas, which largely depend on organic matter produced through photosynthesis (Sibuet and Olu, 1998; Levin, 2005). Similar communities relying on chemosynthetically-produced organic matter have also been recognized around hydrothermal vents and deep-marine organic

enrichment sites associated with sunken animal and plant material (e.g. Smith and Baco, 2003; Bernardino et al., 2010). The dominant animal groups at modern oceanic chemosynthesis-based communities consist of solemyid, lucinid, thyasirid and vesicomid clams, bathymodiolin mussels, abyssochrysooid gastropods and siboglinid tubeworms (e.g. Dando et al., 1991; Sibuet and Olu, 1998; Southward et al., 2001; Sahling et al., 2002, 2003; Taylor and Glover, 2010; Sasaki et al., 2010). Although palaeontological evidence supports the antiquity of some of these groups, especially solemyid bivalves and siboglinid tubeworms (e.g. Little et al., 1999; Little et al., 2004; Peckmann et al., 2005; Hryniewicz et al., 2016), several important seep taxa (vesicomids and bathymodiolins) have currently their earliest records in the Eocene (Little and Vrijenhoek, 2003; Kiel and Little, 2006; Amano and Kiel, 2007; Vrijenhoek, 2013; Kiel and Amano, 2013; Kiel, 2015; Kiel and Hansen, 2015). Seep communities from the latest Cretaceous and the earliest Paleogene are therefore very important for constraining the age of origin of modern seep faunas. There are, however, just a handful of sites from this time interval, including some of the youngest aged Tepee Buttes seeps from the Maastrichtian of the Western Interior

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Seaway, USA (Metz, 2010); the Sada Limestone from the Campanian–Maastrichtian of Shikoku Island, Japan (Nobuhara et al., 2008); Maastrichtian seeps from the James Ross Basin, Antarctica (Little et al., 2015) and the Paleocene Panoche Hills seeps from California, USA (Schwartz et al., 2003). Possible chemosynthesis-dependent communities associated with sunken wood have also been described from the Paleocene of Hokkaido (Amano and Jenkins, 2014; Amano et al., 2015a, 2015b). This paper describes fossiliferous methane seep carbonates and wood-fall occurrences from Paleocene marine sediments from Fossildalen, Spitsbergen, Svalbard. The fauna from the seep carbonates is of moderate diversity and is dominated by the large thyasirid bivalve *Conchocele conradii* Rosenkrantz, 1942, with subordinate protobranch and lucinid bivalves, “naticiform” gastropods and other invertebrates. We present petrographic and geochemical evidence supporting our interpretation of the carbonates as fossil hydrocarbon seep deposits, and discuss the geological, ecological and evolutionary significance of the seep and wood-fall communities.

2. Geological setting

The material studied herein comes from the Central Cenozoic Basin of Spitsbergen (subsequently CCB; Fig. 1). The CCB is a NNW–SSE trending synclinorium, formed in the Paleogene during the strike-slip movement between Greenland and the Barents Sea shelf related to the opening of the Northern Atlantic (Steel et al., 1981; Dallmann, 1999). The basin encompasses nearly 2000 m of Paleocene and Eocene transitional to marine sediments of the Van Mijenfjorden Group, comprising fine- to coarse-grained clastics and subordinate coals (Dallmann, 1999). The fossiliferous carbonates and associated sunken wood layer described in this paper come from the late Paleocene deposits of the Basilika Formation (Major and Nagy, 1972; Manum and Throndsen, 1986; Dallmann, 1999). This represents offshore siltstones and subordinate sandstones, up to 350 m thick, with several thin

volcanogenic clay layers (Dypvik and Nagy, 1978). The benthic foraminiferal fauna of the Basilika Formation indicates restricted offshore shelf to prodelta conditions and oxygen depletion, possibly related to water column stratification (Nagy et al., 2000). The Basilika Formation contains numerous glendonites – pseudomorphoses after carbonate hexahydrate mineral ikaite (Suess et al., 1982) – indicative of cold-water conditions in Spitsbergen during the late Paleocene (Spielhagen and Tripati, 2009).

3. Materials and methods

3.1. Locality information

A proportion of the fossils treated in this paper was previously described by Hägg (1925), Gripp (1927) and Vonderbank (1970). Chronologically the first work dealing with fossiliferous carbonates from the Paleocene of Fossildalen is that of Hägg (1925), material from which is curated at the Naturhistoriska Riksmuseet, Stockholm, Sweden. The specimens were collected at Colesbukta on the southern coast of Isfjorden by the Norwegian mining engineer Arthur Lewin during the summers of 1923 and 1924, and subsequently handed over to Hägg the following winter. The consequence is that Hägg's (1925) locality description is second-hand and rather general, indicating the western side of Colesbukta, 150 m above sea level and about 300–400 m above the base of the Cenozoic. A hand-drawn map of Arthur Lewin stored in Stockholm together with the appearance of the material suggests that Lewin's locality is somewhere around the small valley of Fossildalen. The material of Gripp (1927) was stored in the palaeontological collections of the Universität Hamburg, but was most likely destroyed during WWII (U. Kotthoff, 2015, personal communication). However, Gripp's locality description is helpful for the Fossildalen seep locality identification as he participated in the German 1925 Spitsbergen Expedition and collected the material himself. Gripp states that the

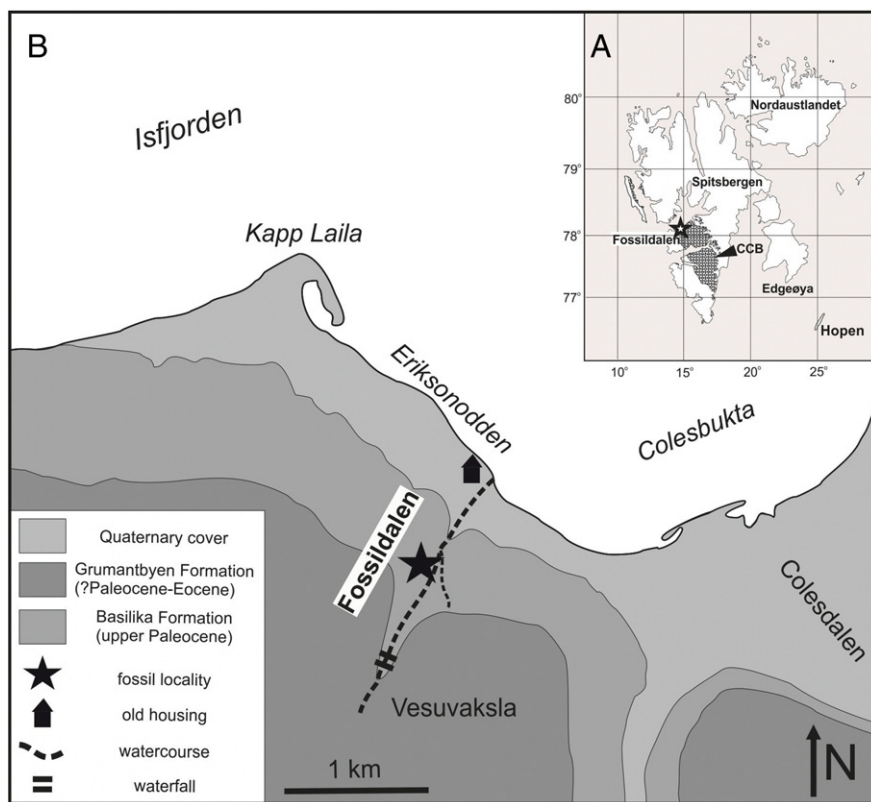


Fig. 1. A) Map of Svalbard with Cenozoic outcrops indicated, CCB stands for Central Cenozoic Basin; B) simplified geological map of the Fossildalen area with the approximate position of the study site and reference points of Gripp (1927) indicated; A) after Nagy et al. (2013); B) after Ohta et al. (1992), lithostratigraphic unit names after Dallmann (1999).

expedition learned from Hägg about Arthur Lewin's discovery a few years before and visited the same locality on the western side of Colesbukta. The site was in a mid-section of a valley with a house close to its mouth entering Colesbukta and waterfalls closing its upper end. The only valley in the area matching this description is Fossildalen. The third collection, made by Vonderbank (1970), is stored in the palaeontological collections of Steinmann-Institut für Geologie, Mineralogie und Paläontologie, Universität Bonn, Germany. Vonderbank did not describe his localities and his work contributes little to the site identification. However, the petrography of the carbonates he found matches that from the former two publications and we conclude he collected at the same site as Lewin and Gripp. It is important to add that Gripp's expedition did not mention any fossils in "four nearby valleys". Vonderbank, on the other hand, also illustrates a "Conchocele-Horizont" somewhere along a 4 km stretch west of Kapp Laila (Vonderbank, 1970, fig. 9).

In the summer of 2015 we re-visited the western side of Colesbukta and located identical fossiliferous carbonates to those described by Hägg (1925) and Gripp (1927) in Fossildalen. We found heavily worn decimetre-sized blocks composed of i) carbonate, ii) siltstone and sandstone with carbonate floats and nodules, and iii) siltstone and sandstone with carbonate-filled *Conchocele* fossils. The great majority of the samples were found in the riverbed of the small river flowing in Fossildalen (Fig. 1); a few weathered carbonate-filled fossils have also been found in scree deposits, approx. 50 m east of the river. No carbonates were found in-situ in the outcropping Basilika Formation sediments forming the riverbanks. Due to ex-situ preservation we are unable to judge whether Fossildalen carbonate blocks and associated fossils come from a single, larger carbonate body or represent remains of several smaller deposit scattered in the succession. Sunken wood environment was identified in-situ in a sandstone bed with abundant plant debris and associated *Conchocele* specimens cropping out along the western side of the valley, approximately 12 m above the riverbed at the position

of 78°5'52.68" N, 14°31'51"59 E (Fig. 2). Fragments of similar sandstones were also common in the riverbed.

The material figured and described in this publication is stored in Naturhistoriska Riksmuseet, Stockholm, Sweden (NRM), Steinmann-Institut für Geologie, Mineralogie und Paläontologie, Universität Bonn, Germany (GPIBo), Natural History Museum, University of Oslo (PMO) and Institute of Paleobiology, Polish Academy of Sciences, Warsaw (ZPAL).

3.2. Palynology and micropalaeontology

One carbonate sample was tested for the presence of palynomorphs for biostratigraphy. The carbonate was dissolved using ca. 10% HCl solution, and the siliciclastic material was removed using a ca. 30% HF solution. A 15 µm sieve and a heavy liquid (ZnCl₂) was then used to separate any remaining mineral particles from the organic material. To extract agglutinated foraminiferal fossils for biostratigraphy, a two-kilogram sample of carbonate cemented sandstone was digested in 10% acetic acid for three weeks. The acid was changed twice a week. The residue was sieved and three fractions between 63 and 500 µm were collected, dried and picked. While benthic foraminifera were common in the residues, no fish teeth or scales were recovered.

3.3. Petrography

A set of uncovered thin sections (48 mm × 28 mm) was prepared in order to identify the main cement phases in the carbonate blocks sampled in 2015, and to interpret their spatial and temporal relationships. Polished slabs were prepared and used to interpret the temporal and spatial relationship between the carbonate and the surrounding siliciclastic rock. Thin sections and polished slabs were also prepared from the wood-rich sandstone layer. The thin sections from all lithologies were subsequently examined in normal and cross-polarized light

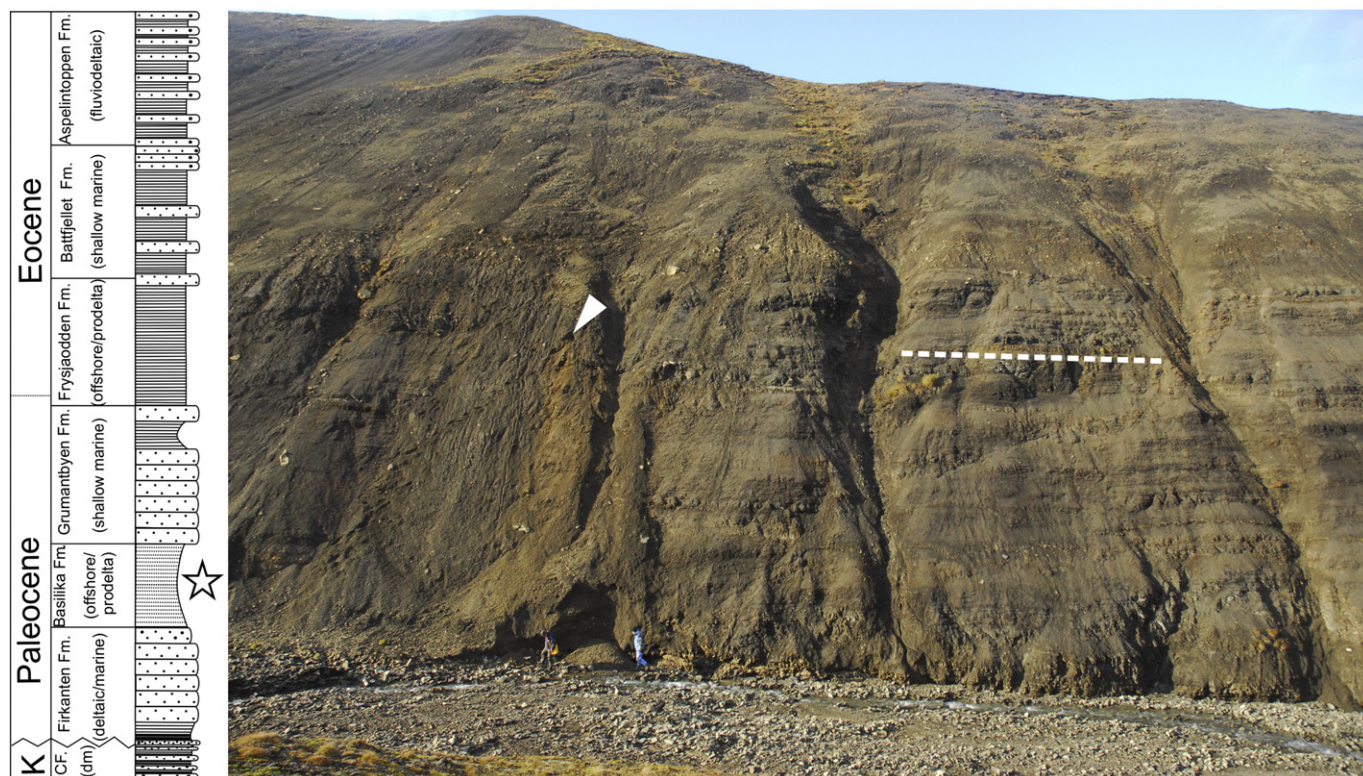


Fig. 2. The assumed locality of Hägg (1925); Gripp (1927) and Vonderbank (1970), sampled during 2015 field season. The carbonates come exclusively from the riverbed, with the uppermost blocks found approximately where the geologists are standing. The stippled line marks the outcropping bed of sunken wood-rich sandstone, with approximate sampling point indicated by the arrow. The lithostratigraphic column of Paleogene succession of Central Cenozoic Basin after Spielhagen and Tripathi (2009), the star marks approximate position of the sampled locality. CF – Carolinefjellet Formation; dm – deep marine. Depositional environments of particular formations after Helland-Hansen (2010).

using an optical microscope and photographed with a digital camera. The terminology for carbonate cement phases used herein follows that of Folk (1959) and Peckmann and Thiel (2004). X-ray diffraction (XRD) pattern analysis to determine the mineralogy of the carbonate phases was performed using an Ultima IV (Rigaku) machine at Kanazawa University, Kanazawa, Japan.

3.4. Stable carbonate carbon and oxygen isotopes

Samples for stable carbonate carbon and oxygen isotope analyses of the carbonates sampled in 2015 were hand drilled from different phases to produce powders, or mechanically crushed using pliers, and afterwards analysed using Thermo Scientific Finnigan GasBench II/ Isotope ratio mass spectrometry (IRMS: Delta V Advantage) at Kanazawa University. Measured values were corrected using two points calibration with NBS19 and LSVEC. The standard deviations (1σ) of replicate analyses of NBS19, LSVEC and a lab standard were better than 0.08‰ and 0.12‰ for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$, respectively. All carbon and oxygen isotopic values are expressed in the conventional δ notation relative to V-PDB (the Vienna Pee Dee Belemnite) standard.

3.5. Lipid biomarkers

Selected Fossildalen carbonate samples collected in 2015 were cut and washed with distilled water, methanol (MeOH), and then dichloromethane (DCM). The samples were then crushed and ground into powder, and lipids were extracted from 20 g of the powdered samples by ultrasonication in DCM:MeOH (7:3, v:v) for 15 min. The extracts were centrifuged, and the supernatants were decanted. The extraction process was repeated more than twice. Acid-activated copper was added to remove elemental sulfur. Lipids were separated using silica gel column chromatography into hydrocarbon, aromatic, ketone, and polar fractions. The hydrocarbon fraction was injected into a gas chromatograph-mass spectrometer (GC-MS) (SHIMADZU GC-2010 coupled with GCMS-QP2010) equipped with a HP-5MS capillary column (30 m \times 0.25 mm i.d., 0.25 μm film thickness, Agilent Technologies), at the Laboratory of Evolution of Earth Environment, Kanazawa University, Japan. Helium was used as the carrier gas. The GC oven temperature was programmed as follows: sample injection at 50 °C (splitless); ramp up to 120 °C at 30 °C/min; ramp up to 310 °C at 3.0 °C/min; then 15 min isothermal.

Compound-specific stable carbon isotope analysis of the extracted hydrocarbons was performed using an isotope-ratio mass spectrometer (Thermo Scientific Delta V Advantage) interfaced with a gas chromatograph (Trace GC Ultra) through a combustion furnace (GC Isolink), at the Laboratory of Evolution of Earth Environment, Kanazawa University. Combustion was carried out using a combustion reactor for CN at 1030 °C. The sample was injected splitless onto a DB-5MS capillary column (60 m \times 0.25 mm i.d., 0.1 μm film thickness, Agilent Technologies) at 50 °C using Helium as the carrier gas. After 5 min, the GC oven temperature was raised to 120 °C at 30 °C/min, and then to 285 °C at 5 °C/min. Finally, the oven temperature was raised to 310 °C at 30 °C/min and kept at 310 °C for 8 min. Carbon isotopic composition was expressed in the delta notation ($\delta^{13}\text{C}$ ‰ vs. V-PDB). Precision was checked analyzing a standard *n*-alkane mixture (C_{17} , C_{18} , C_{20} , C_{24} , C_{28} , and C_{32}) with known isotopic compositions before analyzing the sample.

4. Results

4.1. Age of the deposits

The palynological material obtained from one carbonate sample is dark-brown to black and comprises moderately well preserved dinoflagellate cysts, pollen grains, spores, xylem and amorphous organic matter particles. The dinocysts are subordinate, nonetheless we were able to identify five taxa: *Cerodinium dartmoorium*, *Cerodinium striatum*,

Oligosphaeridium complex, *Palaeoperidinium pyrophorum* and *Spiniferites ramosus* (Fig. 3). This dinoflagellate assemblage allows us to precisely date the sample. The co-occurrence interval for *C. dartmoorium*, *C. striatum* and *P. pyrophorum* is the upper part of the D3 and the lower part of the D4 dinoflagellate cyst biozones of the upper Paleocene (Thanetian) (Fig. 4; Costa and Manum, 1988). The assemblage is very similar to that previously described from the same locality (Manum and Thondsen, 1986; Fig. 4, p. 113). However, these authors suggested an age closer to the lower/upper Paleocene boundary (upper D2 zone). This difference in age interpretation results from the presence of *C. striatum*, which occurs until the lower part of the D4 zone according to (Powell, 1992; up to the upper D2 in Manum and Thondsen, 1986), and the appearance of *C. dartmoorium* in the upper D3 according to (Powell, 1992; in the upper D2 zone in Manum and Thondsen, 1986).

The preservation of the foraminiferal specimens in the carbonate cemented sandstone sample is mostly excellent, owing to the authigenic precipitation of the carbonates, as observed in other, older, fossil seeps from Spitsbergen (Hjálmarsson et al., 2012). The assemblage is entirely agglutinated with medium diversity. Of 485 specimens picked for micropalaeontological analysis, 28 taxa are identified in the sample. The dominant species are *Haplophragmoides* spp. and *Labrospira turbida*. Five species are stratigraphically important: *H. porrectus*, *H. walteri*, *Reticulophragmoides jarvisi*, *Verneulinoides subeoceanus* and *Marssonella oxycona* (Fig. 3), indicating that the sample is of late Paleocene–early Eocene age (Fig. 4; Charnock and Jones, 1990).

A stratigraphic atlas of foraminifera by King (1989) compares microfossil marker events in the Paleocene of the North Sea to the dinoflagellate zones of Costa and Manum (1988) (see above). The foraminiferal assemblage found in Fossildalen is most consistent with biozone NSB2, equating to the lower Eocene. However, because the Fossildalen palynological material indicates biozones D3–D4 (upper Paleocene) it seems that the North Sea foraminiferal biozonation scheme of King (1989) does not work for this locality on Spitsbergen.

4.2. Petrography of the carbonates

Fossildalen site yields decimetre-sized carbonate blocks, and carbonate floats and nodules within sandstone blocks (Fig. 5A). The dominant phase forming the carbonates is micrite (m) containing quartz sand grains (Fig. 5B), rare chert pebbles, volcanogenic grains, and localized accumulations of fecal pellets. Carbonates can also be found as infill within articulated *Conchocele* fossils occurring in the sandstone blocks (Fig. 5C). Cavities within carbonates are rare and are either located within geopetal structures inside articulated *Conchocele* specimens (Fig. 5C) or centimetre-sized cavities within larger blocks of carbonate (Fig. 5D). The oldest mineral phase lining the cavities is a discontinuous pyrite layer, associated with corrosion and accumulation in insoluble residue (pyr, Fig. 5E). This is followed by authigenic carbonate crusts, composed of a discontinuous layer of yellow calcite (yc; Fig. 5E) and botryoidal calcite (bc; Fig. 5F). The individual crystallites forming the botryoids are fibrous and elongated, have feather-like culminations and contain inclusion-rich bands (Fig. 5F).

The carbonate crusts lining geopetal structures within articulated *Conchocele* specimens from the siltstone blocks are sometimes fractured and separated from the shell (sh), with the fractures sealed by translucent microspar (ms; Fig. 6A). A similar phase post-dates the formation of botryoidal calcite and lines the outer surface of the botryoids (Fig. 6B). The phase post-dating the formation of the translucent microspar from articulated *Conchocele* specimens from the sandstones is a layered clastic fill (cl; Fig. 6B, C). The clastic fill occasionally contains fragments of the botryoidal carbonate lining the inner surface of the shell; some fragments are covered with a thin layer of microspar (Fig. 6D). The infilling pattern of *Conchocele* with authigenic carbonate crust followed by clastic fill can recur (Fig. 6E). The last phase filling the cavities within articulated *Conchocele* specimens is equant calcite spar (eq; Fig. 6F).

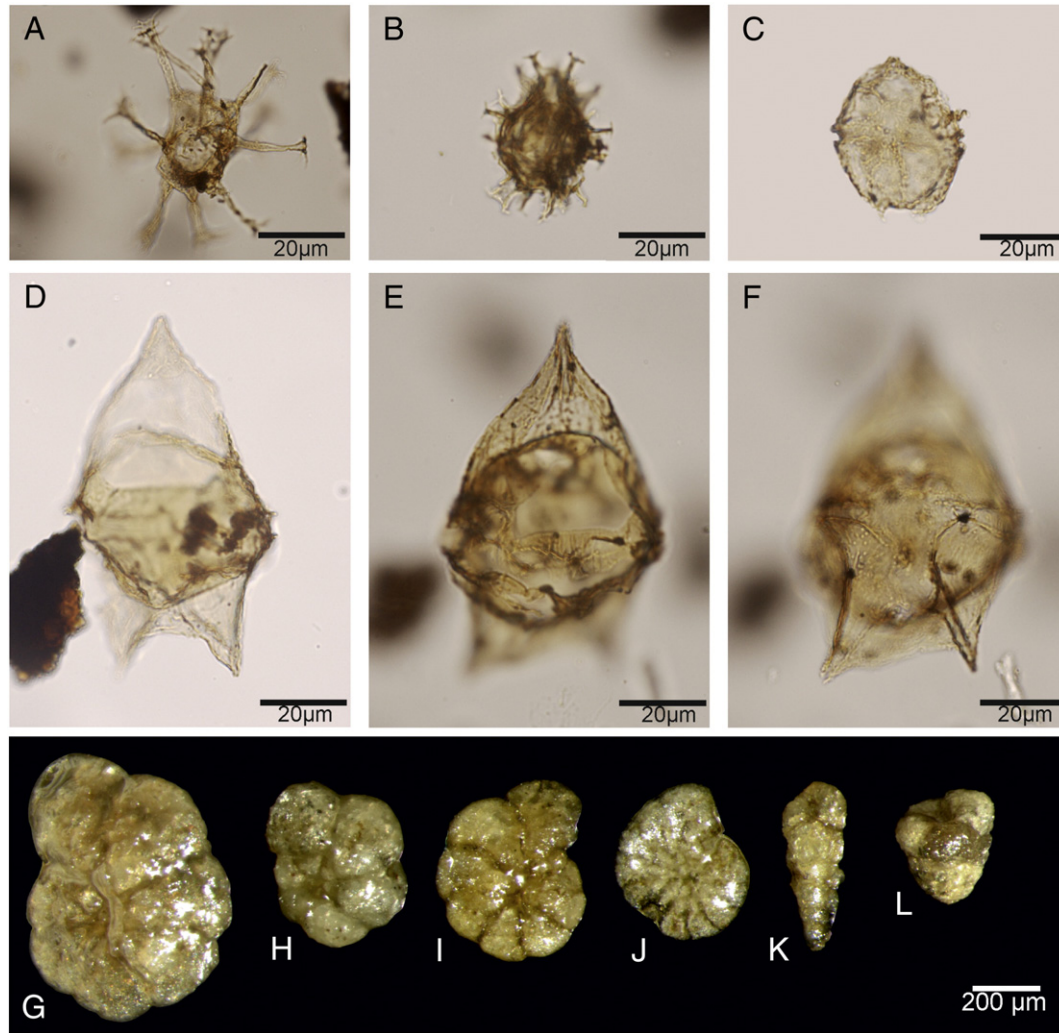


Fig. 3. Dinoflagellate cysts and foraminifera recorded in this study. A) *Oligosphaeridium* complex, ZPAL V.50/1; B) *Spiniferites ramosus*, ZPAL V.50/8; C) *Palaeoperidinium pyrophorum*, ZPAL V.50/3; D) *Cerodinium dartmoorium*, ZPAL V.50/3; E–F) *Cerodinium striatum*, ZPAL V.50/5; G) *Labrospira turbida*; PMO 221.881/1; H) *Haplophragmoides porrectus*; PMO 221.881/6; I) *Haplophragmoides walteri*; PMO 221.881/15; J) *Reticulophragmoides jarvisi*; PMO 221.881/13; K) *Verneuilinoides subeocaenus*; PMO 221.881/3; L) *Marssonella oxycona*; PMO 221.881/4.

The inner walls of the cavities from the carbonate blocks are lined with carbonate crusts similar to those from the geopetal structures in *Conchocele* specimens. A cement phase post-dating the formation of the authigenic carbonate crusts is often silica, represented by

chalcedony (ch; Fig. 7A) and microcrystalline quartz, postdated by macrocrystalline quartz (miq and maq, respectively; Fig. 7B). The innermost space of the cavities is, when present, filled with equant calcite spar similar to that from the geopetal structures within *Conchocele* specimens (Fig. 7A). Some carbonate blocks contain a lot of wood, which is broken to centimetre-sized fragments and can be heavily mineralized by carbonate, and, locally, by pyrobitumen (Fig. 8A). Some fragments of wood contain oval borings up to 20 mm in diameter (Fig. 8B, C), which are straight and long (Fig. 8D), and filled with carbonate containing fecal pellets and agglutinated tubes. When possible to observe, the borings are oriented parallel to the wood grain.

4.3. Stable carbon and oxygen isotopes of carbonates

The stable carbon and isotope composition of the Fossildalen carbonates is given in Table 1 and Fig. 9. Micrite is heavily depleted in ^{13}C , with $\delta^{13}\text{C}$ values varying between -49.4 and -38.8% . Botryoidal carbonate has similar to slightly higher $\delta^{13}\text{C}$ values as the micrite, varying between -42.9 and -32.5% . Both phases are similar with respect to their $\delta^{18}\text{O}$ values, varying between -6.0 and -3.7% for the micrite and -5.9 and -4.4% for the botryoidal carbonate, respectively. The equant calcite spar filling some voids is less depleted with respect to the heavy carbon isotope than both the micrite and the botryoidal carbonate ($\delta^{13}\text{C}$ value of -22.9%). This phase is very heavily depleted

SYSTEM	SERIES	STAGE	DINOFLAGELLATE CYST BIOZONES
PALEOGENE	PALEOCENE	UPPER	THANETIAN
			D5a
			D4
			D3
			D2
			Cerodinium dartmoorium
			Cerodinium striatum
			Palaeoperidinium pyrophorum
			Oligosphaeridium complex
			Spiniferites ramosus

Fig. 4. Stratigraphic ranges for the recorded dinoflagellate cyst taxa and proposed age of the studied sample (grey rectangle).

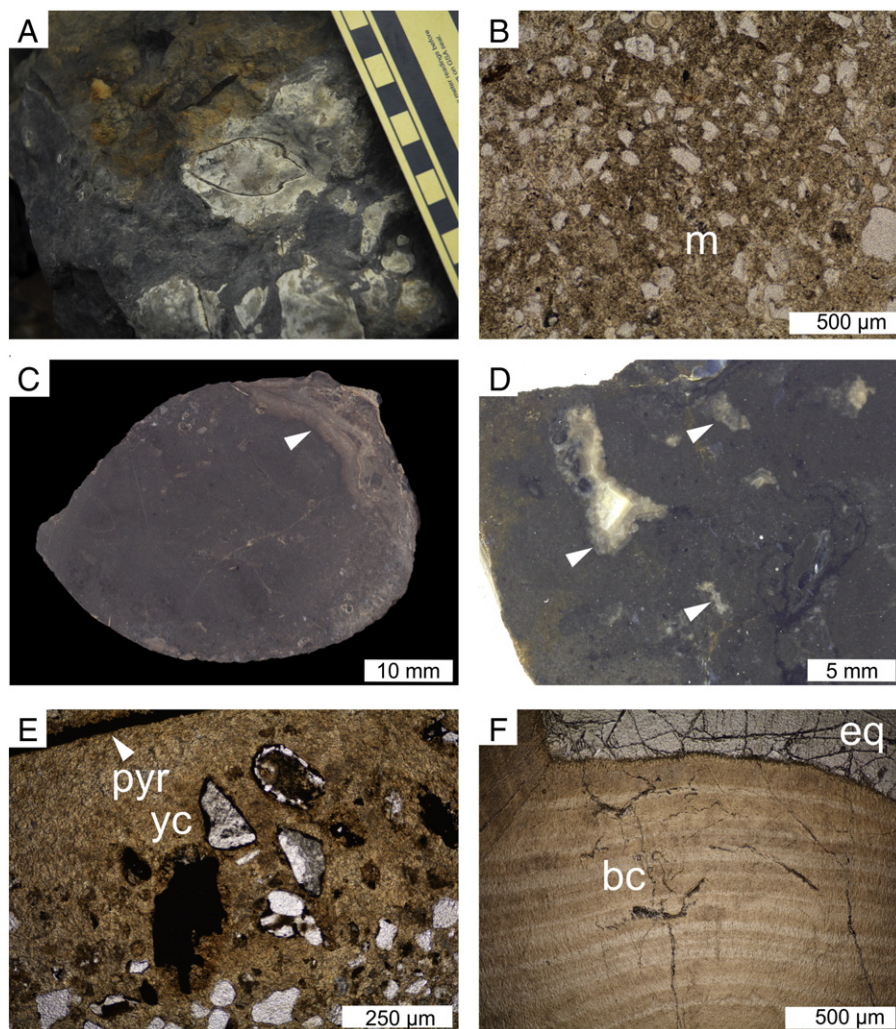


Fig. 5. Petrography of the Fossildalen seep carbonates. A) Micritic carbonate nodules with bivalve fossils floating in the surrounding siltstone, scale bar 1 cm; B) typical appearance of Basilika Formation carbonate in a thin section; micrite (m) hosting numerous quartz sand grains, normal-polarized light, NRM-PZ Mo 149161B; C) polished micrite-filled *Conchocele* extracted from sandstone block; arrow points to a geopetal structure filled with authigenic cements, NRM-PZ Mo 149153A (the sample was subsequently destroyed and used to prepare a thin section); D) polished slab of a carbonate block showing grey micrite with sparse and small cavities (arrows) filled with carbonate cements; PMO 226.818 (the block was subsequently used to prepare a thin section); E) corroded pyrite-rich zone (pyr) between the micrite and botryoidal cement with quartz grains floating within yellow calcite (yc), normal-polarized light, NRM-PZ Mo. 149153b-1; F) botryoidal carbonate filling the geopetal structure, normal-polarized light, ZPAL V.48/1.

with respect to the heavy oxygen isotope ($\delta^{18}\text{O}$ of -17.7‰). The shell samples *Conchocele* specimens are only slightly depleted in heavy carbon and oxygen isotopes ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values around -6.0‰ , respectively).

4.4. Molecular fossils and their stable carbon isotope composition

Total ion chromatogram of the hydrocarbon fraction obtained from the Fossildalen carbonates is shown in Fig. 10. Predominant hydrocarbons comprise normal alkanes, pristane, and phytane. No odd or even chain length preference for n-alkanes were detected. Moderate amount of C_{25} -isoprenoid 2,6,10,15,19-pentamethylcosane (PMI) is contained in the sample. The compound-specific stable carbon isotope analysis of the PMI revealed $\delta^{13}\text{C}$ values of ca. -100‰ .

4.5. Petrography of the wood-rich sandstone bed

The wood-rich sandstone bed is fine- to medium-grained, composed predominantly of quartz with a fine admixture of chert fragments (Fig. 11A). The outer surface of the blocks is covered with a rusty crust, whereas fresh surfaces are dark grey to black. The pore space of the sandstone is occluded with a mixture of clay minerals and pyrite (Fig.

11A); the latter constituting up to 50% of the total pore space available. The sandstone is mostly devoid of carbonate grains, but locally it contains patches of carbonate cement, which is macroscopically undetectable but revealed by reaction with HCl. The matrix locally contains sparse accumulations of brown fecal pellets up to 0.5 mm in diameter (Fig. 11B). Wood fragments are very common in the slides. The vast majority are unidentified fragments and chips a few mm in diameter. The inner structure of the small chips is well preserved and it is possible to distinguish individual wood cells (Fig. 11C). The outer surface of the wood chips is usually heavily worn and covered with a pyrite crust (Fig. 11D). Larger fragments of wood are altered beyond identification, often being heavily weathered and crumbling when touched in the field.

4.6. Macrofaunal content

The Fossildalen carbonates and wood-rich sandstone bed contain a macrofaunal assemblage of moderate diversity and abundance, composed predominantly of molluscs with subordinate crustaceans, brachiopods and worm tubes. A proportion of the macrofossils from the Fossildalen carbonates were previously identified and figured by Hägg (1925), Gripp (1927) and Vonderbank (1970). We present the original

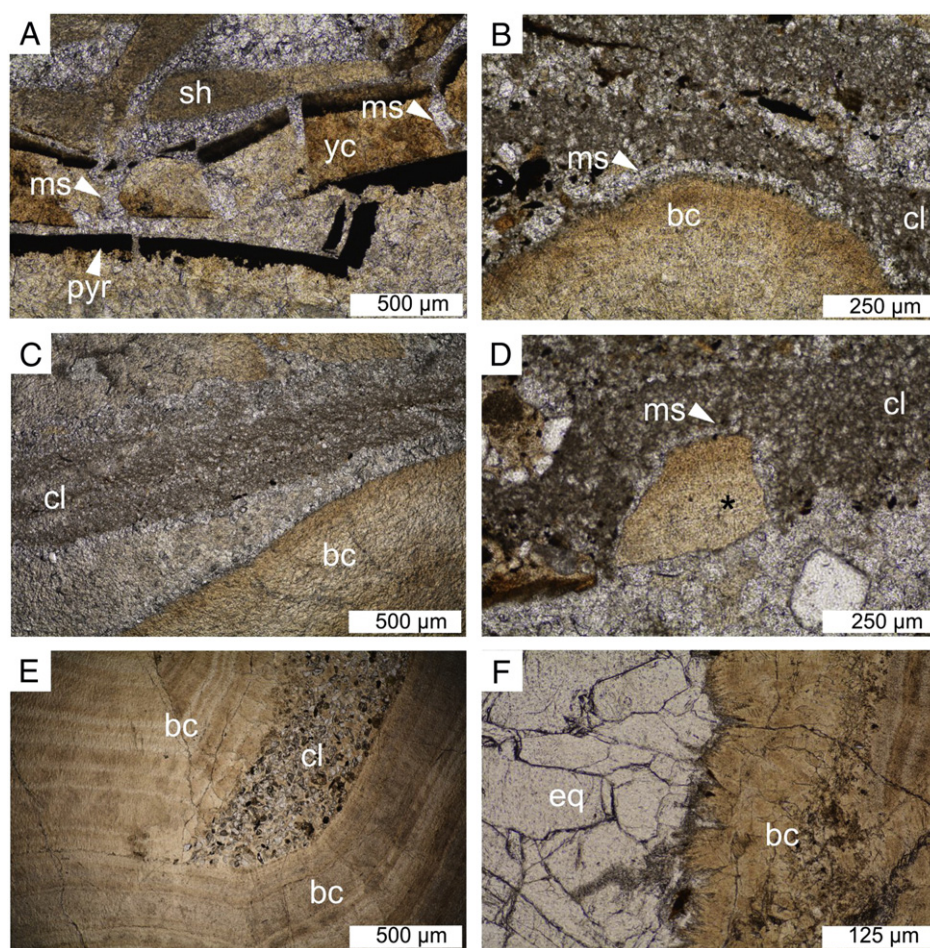


Fig. 6. Displaced carbonate crust from carbonate-filled *Conchocele* from Basilika Formation siltstones. A) Fractured pyrite (pyr) and yellow calcite crust (yc) separated from *Conchocele* shell (sh) by cracks filled with translucent microspar (ms), normal-polarized light, NRM-PZ Mo 149153A; B) botryoidal carbonate (bc) covered with thin layer of translucent microspar (ms) with the innermost void filled with clastic fill (cl), normal-polarized light, NRM Mo 149153A; C) layered clastic fill (cl) covering the botryoidal carbonate (bc), normal-polarized light, NRM-PZ Mo 149153A; D) fragment of botryoidal carbonate (asterisk) floating within layered clastic filling (cl) of the geopetal structure, normal-polarized light, NRM-PZ Mo 149153A; E) pocket of clastic fill (cl) within the botryoidal carbonate (bc) followed by subsequent re-precipitation of botryoidal carbonate, normal-polarized light, ZPAL V.48/1; F) a botryoidal carbonate (bc) followed by equant calcite spar (eq), normal-polarized light, ZPAL V.48/1.

identifications and source together with our preliminary taxonomic re-interpretations in Table 2. Systematic work on the museum specimens and those collected in 2015 is currently ongoing.

The fauna is dominated by bivalves. Gastropods, crustaceans and worm tubes are less abundant but locally common; only few brachiopod specimens have been found (Table 2). The dominant bivalve is the large thyasirid *Conchocele conradii*, occurring in mass-accumulations of specimens up to 85 mm long (Fig. 12A). The species occurs also in the surrounding grey siltstones of the Basilika Formation. These

specimens have carbonate infillings, their shells are sometimes damaged, and the surrounding siltstones exhibit flow structures and sedimentary deformation structures characteristic of gravity flow deposits. *Conchocele conradii* is the only macrofossil found in the wood-rich sandstone layer, where virtually all specimens are deformed and fractured. A somewhat less common bivalve from the carbonates is a small (up to 16.5 mm long) heterodont species, which Vonderbank (1970) classified as a species of the lucinid *Anodontia* (Fig. 12B). This species has elongated anterior adductor muscle scar which could indicate a lucinid, and a

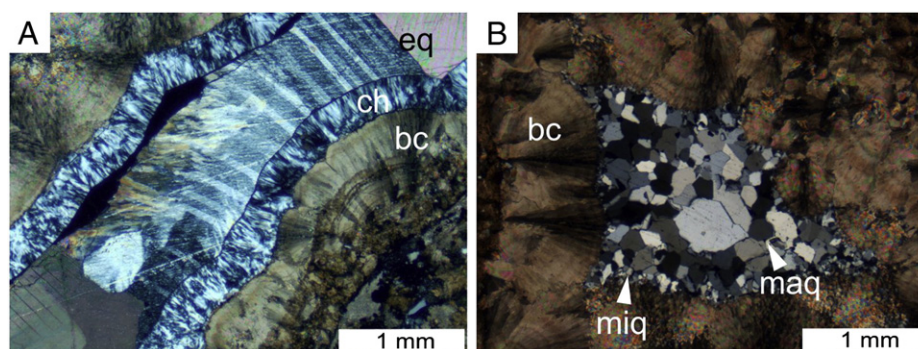


Fig. 7. Silification of Fossildalen seep carbonates. A) Chalcedony (ch) following the botryoidal carbonate (bc) and preceding the precipitation of equant calcite spar (eq) within the vug, crossed-polarized light, PMO 226.816; B) micro- (miq) and macro- (maq) crystalline variety of quartz filling the innermost space of the vug, crossed-polarized light, PMO 226.818.

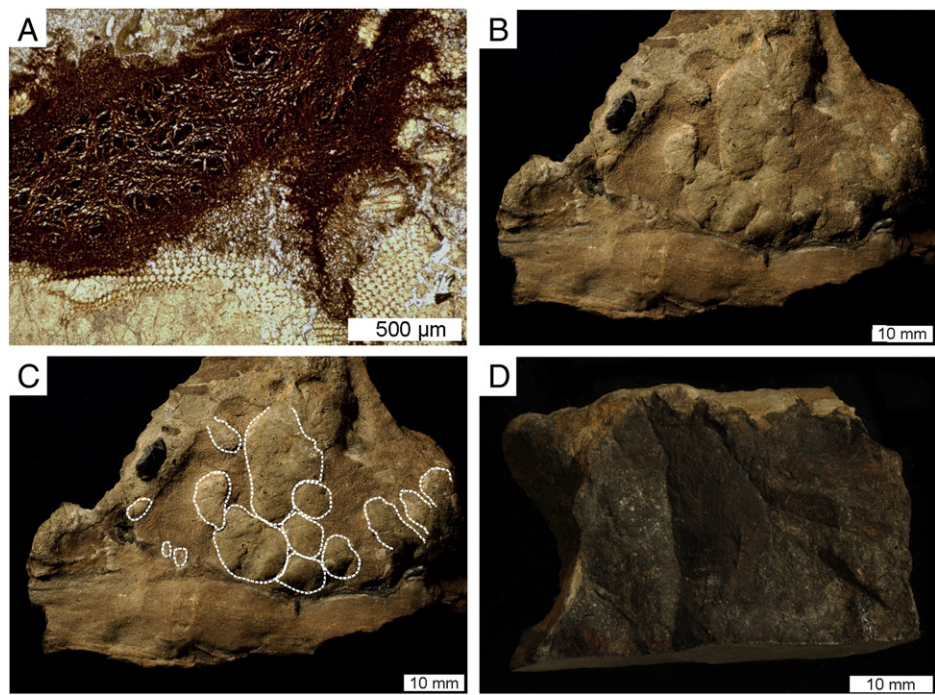


Fig. 8. Preservation of the wood in Fossildalen seep carbonates. A) Petrographic thin section showing fragmented and carbonate-replaced wood partially impregnated by pyrobitumen, plane-polarized light, ZPAL V.48/2; B, C) heavily bored wood fragment, with carbonate-filled, unlined borings, ZPAL V.48/3; D) carbonate-filled boring oriented parallel to wood grain; with residual wood lining the boring, ZPAL V.48/4.

weakly oval shape and fine commarginal growth lines reminiscent of myrteine lucinids from deep-water seeps (Kiel, 2013). We were able to find five specimens of a wood boring pholadoid bivalve species from wood in the carbonates, either a xylophagain or a teredinid (Fig. 12C); more shells which could represent this species are visible on cross sections of the some borings in the wood. Fairly common bivalves in the carbonates are elongated protobranchs, probably which could represent nuculanids, malletiids and yoldiids (Fig. 12D). A less common bivalve is a species of a mussel (Fig. 12E). This is elongated and has a pointed umbo, thus it does not resemble a typical seep bathymodiolin mussel and is more similar to shallow marine mussels, like *Inoperma*. Similarly shaped species have been illustrated from the Miocene La Piedra seep in Venezuela by Kiel and Hansen (2015) and interpreted as *Brachidontes* sp.; the comarginal ornament exhibited by our species precludes us from placing it within this genus. The species of a heterodont bivalve identified as a species of *Astarte* by Hägg (1925) and Gripp (1927) has an elongated shell and a sunken lunule (Fig. 12F), characters common among some astartiids so we tentatively agree that this species is a possible astartiid.

The macrofauna from the carbonates includes four species of gastropods, which are generally less common in the material than the bivalves. The most abundant gastropod species is a low-spined

“naticiform” interpreted by Vonderbank (1970) as a species of *Ampullonatica* (Fig. 12G). This species occurs in the carbonate samples which are rich in wood, often directly on the wood. We tentatively attribute the morphological term “naticiform” to this gastropod (either naticid or ampullospirid), due to lack of evidence allowing for a more precise identification. The other gastropods are rarer than the “naticiform” species. A large, high-spined gastropod was interpreted by Gripp (1927) as a species of *Chenopus*, which is younger synonym of *Aporrhais* (Fig. 12H). We agree with the preliminary interpretation of this species as an aporrhaid, although due to the poor preservation a more detailed identification is currently not possible. The other gastropods include a cylichnid (Fig. 12I) and a possible neogastropod (Fig. 12J).

The carbonate samples rich in wood, contain locally abundant disarticulated crustacean fossils. These include carapaces (Fig. 12K) and abundant appendages, chela, limbs and telson fragments. The disarticulated fossils were previously interpreted by Vonderbank (1970) as belonging to a single species he described as the new

Table 1
Stable carbon and oxygen isotope compositions of Fossildalen seep carbonates.

Sample no.	$\delta^{13}\text{C}$ ‰ (V-PDB)	$\delta^{18}\text{O}$ (V-PDB)	Petrography
NRM-PZ Mo149153B-C1	−37.7	−4.6	Botryoidal calcite
NRM-PZ Mo149153B-C2	−33.0	−5.8	Botryoidal calcite
NRM-PZ Mo149153B-C3	−42.9	−4.4	Botryoidal calcite
NRM-PZ Mo149153B-C4	−32.5	−5.9	Botryoidal calcite
PAL-C5	−22.9	−17.7	Euhedral calcite
PAL-M1	−38.8	−6.0	Micrite
PAL-M2	−40.1	−3.7	Micrite
PAL-M3	−42.9	−5.0	Micrite
PAL-M4	−45.9	−5.3	Micrite
PAL-M5	−49.4	−4.8	Micrite
NRM-PZ Mo15946-S1	−5.8	−5.9	Shell
PAL-S2	−5.7	−6.0	Shell

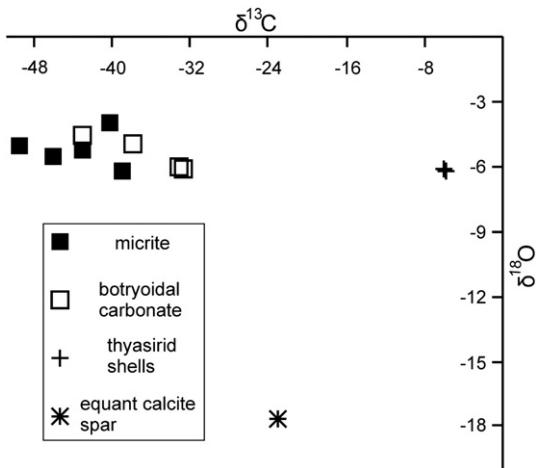


Fig. 9. Cross plot of $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ composition of Fossildalen seep carbonates.

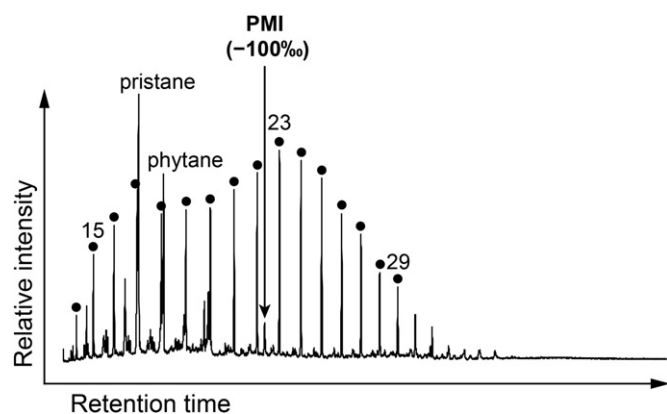


Fig. 10. Total ion chromatogram of the hydrocarbon fraction obtained from Fossildalen seep carbonates. Closed circles indicate *n*-alkanes, and numbers above them indicate carbon numbers. PMI, pentamethylcosane. The compound-specific stable carbon isotopic composition of PMI is shown in parentheses as $\delta^{13}\text{C}$ value vs. V-PDB.

galatheid decapod *Galathea spitzbergica*. We agree the fossils are of galatheoid origin, although the ornament of the carapace, especially the dorsally-ridged rostrum, suggests that the species belongs to the munidids rather than to the galatheids (Ahyong et al., 2010). The brachiopods are represented by a single terebratulide species, assigned by Gripp (1927) to *Terebratulina* sp. Preliminary examination of our material suggests that the brachiopods belong to a short-looped terebratulid rather than a long-looped terebratulid, as indicated by the lack of dorsal septum. The shape of the beak and foramen, and the smooth shell surface excludes the genus *Terebratulina*. The characters mentioned above as well as two-layered shell show that the investigated specimens might be attributable to the genus *Pliothyridina*. The remaining macrofossil species is a *Spirorbis* worm tube (Vinn et al., 2013), attached to the surface of large mytilid (Fig. 12E). In addition, the wood rich carbonates contain numerous agglutinated tubes up to 3 mm in diameter.

5. Interpretations

5.1. Paleocene hydrocarbon seepage recorded in the Basilika Formation

The available evidence, including the cement phases and heavily depleted $\delta^{13}\text{C}$ composition of the carbonates, and the lipid biomarker PMI, are consistent with a hydrocarbon seep origin for the Fossildalen carbonates (e.g. Peckmann et al., 1999; Boetius et al., 2000; Peckmann and Thiel, 2004; Kiel and Peckmann, 2007). The investigated carbonates were formed mostly by carbonate authigenesis within background muds and sands related to the anaerobic oxidation of seeping methane (AOM; Boetius et al., 2000). The presence of highly ^{13}C -depleted PMI (ca. -100‰) in the sample indicates the existence of anaerobic methane-oxidizing archaea (Peckmann and Thiel, 2004). The archaea are responsible for the AOM with sulfate-reducing bacteria. The very low $\delta^{13}\text{C}$ values of the investigated carbonates (approaching -50‰) and that of PMI (as low as -100‰) indicate that biogenic methane was the primary source of carbon for the AOM.

Micrites are sometimes interpreted as initial carbonate precipitates at fossil seep sites (e.g. Campbell et al., 2002), and the Fossildalen seep micrites may have formed prior to the botryoidal carbonates. The available data show that the micrites of Fossildalen seep carbonates are more ^{13}C -depleted than the botryoidal cements. This could represent sampling bias, but it could also indicate that both phases formed in a partially closed system. The $\delta^{18}\text{O}$ values of the Fossildalen carbonates mostly range between -6.2 and -3.7‰ , and partially overlap values found in the glendonites common in the Basilika Formation (Spielhagen and Tripathi, 2009). The presence of glendonites indicates that the Fossildalen seep carbonates formed in cold water. However, the low $\delta^{18}\text{O}$ values of seep carbonate cements indicate relatively warm and/or brackish conditions. Diagenetic resetting of oxygen isotope values should therefore be considered. Indeed, the carbonate cements (as shown by XRD) are mainly composed of calcite, with only minor amounts of aragonite present, which also indicates diagenetic alteration. A single extremely low $\delta^{18}\text{O}$ value (-17.7‰) was likely related to freshwater reflux through the Basilika Formation, as has been suggested for other fossil seep

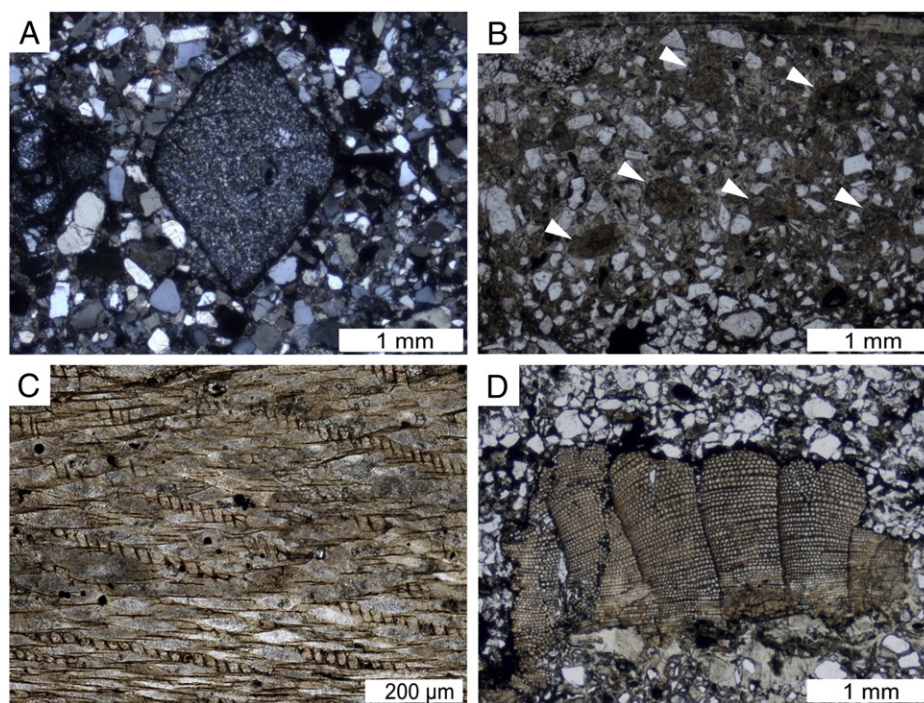


Fig. 11. Petrography of wood-bearing sandstones. A) Chert pebbles floating within pyrite-bearing quartz sandstone, cross-polarized light, PMO 226.835; B) fecal pellets (arrows) dispersed within the bivalve-bearing sandstones, normal-polarized light PMO 226.834; C) taphonomy of the wood showing well-preserved wood cells, normal-polarized light, PMO 226.835; D) a pyrite-encrusted wood chip floating within the sandstone; normal-polarized light, PMO 226.835.

Table 2
List of the macrofossil taxa from the Fossildalen seep carbonates identified during our study, with the identification of Hägg (1925); Gripp (1927) and Vonderbank (1970) given, and our preliminary re-interpretations of their systematic position. Original spelling maintained.

Taxon by Hägg (1925)	Taxon by Gripp (1927)	Taxon by Vonderbank (1970)	Interpretation proposed in this study	Frequency
—	<i>Sabellaria</i> -like worm tube	—	Agglutinated tubes	Many
<i>Natica</i> spec. 1	<i>Natica</i> sp.	<i>Ampullonatica isfjordensis</i>	"Naticiform" gastropod sp.	Many
<i>Natica</i> spec. 2	<i>Natica</i> sp.	<i>Ampullonatica isfjordensis</i>	"Naticiform" gastropod sp.	Many
<i>Natica</i> spec. 3	<i>Natica</i> sp.	<i>Ampullonatica isfjordensis</i>	"Naticiform" gastropod sp.	Many
? <i>Gibbula</i> spec.	—	—	Aporrhaidae sp.	2
—	<i>Chenopus</i> (Arrhoges) sp.	<i>Chenopus gracilis</i> Koenen	Aporrhaidae sp.	2
—	—	<i>Arca</i> sp.	Arcidae sp.	1
<i>Astarte</i> spec.	<i>Astarte</i> sp.	—	Astartiidae? sp.	1
? <i>Kellia</i> sp.	—	—	Bivalvia sp.	Many
<i>Thyasira bisecta</i> Conrad	—	<i>Conchocele conradii</i> Rosenkrantz	<i>Conchocele conradii</i> Rosenkrantz	Dominant
—	—	<i>Cylichna discifera</i> v. Koenen	Cylichnidae sp.	1
<i>Galathea</i> spec.	<i>Galathea spitzbergensis</i> n. sp.	<i>Galathea spitzbergica</i> Gripp	Munididae sp.	Few
<i>Lucina</i> sp.	<i>Thyasira</i> sp. 2	<i>Anodontia spitzbergensis</i> n. sp.	Myrteinae sp.	Many
—	—	<i>Modiolus haumiensis</i> (Rosenkrantz)	<i>Inoperna?</i> sp.	1
—	—	<i>Mytilus plenicostratus</i> n. sp.	<i>Inoperna?</i> sp.	3
<i>Nassa</i> spec.	—	—	Neogastropoda sp.	2
<i>Xylophaga</i> spec.	—	—	Pholadoidea sp.	1+
<i>Lamellibranchiate</i> 1	—	—	Protobranchia spp.	Many
<i>Lamellibranchiate</i> 2	—	—	Protobranchia spp.	Many
<i>Nuculana</i> spec. 1	<i>Portlandia</i> sp.	<i>Nuculana</i> (<i>Jupiteria</i>) <i>haeggi</i>	Protobranchia spp.	Many
<i>Nuculana</i> spec. 2	<i>Portlandia</i> sp.	<i>Nuculana</i> (<i>Jupiteria</i>) <i>haeggi</i>	Protobranchia spp.	Many
—	—	<i>Yoldia</i> sp.	Protobranchia spp.	Many
—	<i>Terebratulina</i> sp.	—	<i>Pliothyra?</i> sp.	Few
—	—	—	<i>Spirorbis</i> sp.	1

deposits (Agirrezabala et al., 2013). This is not surprising because fresh water can penetrate marine sediments tens of kilometres offshore (Kooi and Groen, 2001), and the whole Paleogene succession on Svalbard was deposited in relative proximity of land masses (e.g. Helland-Hansen, 2010).

The micrite which is the principal component of the investigated carbonates typically forms during the diffusive rather than advective seepage (e.g. Campbell et al., 2002, 2008; Kiel and Peckmann, 2008) and its prevalence indicates that this mode of seepage contributed to the formation of investigated carbonates. Consequently, rare cavities within micrite and geopetal structures within the articulated *Conchocele* shells are indicative of localized focused flow and faster carbonate cementation (e.g. Krause et al., 2009). The silica (re-precipitated as chalcedony and two varieties of quartz) post-dating the carbonate crusts was most likely mobilized from siliceous shells (e.g. diatoms, radiolaria or sponge spicules) during a rise of alkalinity due to AOM (e.g. Kuechler et al., 2012). Significant amounts of silica are dissolved during episodes of higher fluid flux, when gas supersaturation favours bubble formation and subsequent CO₂ degassing, which further increases the alkalinity. Subsequent silica re-precipitation occurs during episodes of waning fluid flux and decrease of the alkalinity (Smrzka et al., 2015). Therefore, the silification of the Fossildalen seep carbonates indicates fluctuations of seepage intensity.

The yellow calcite lining the inner surfaces of some of the cavities is a carbonate phase associated specifically with fossil seep carbonates (e.g. Beauchamp and Savard, 1992; Peckmann et al., 2002; Hammer et al., 2011). It might be formed due to the recrystallization of a yellow aragonite precursor, precipitated in the immediate vicinity of the methanotrophic consortia participating in AOM (Hagemann et al., 2013). Its presence in the Fossildalen seep carbonates indicates localized centres of AOM, for example in voids and conduits filled with methane. The botryoidal carbonate cements are common in (but not exclusive to) fossil seep carbonates and indicate rapid precipitation from carbonate-saturated solution (e.g. Peckmann and Thiel, 2004). The fibrous appearance and feather-like culminations of the botryoidal cements (which was diagenetically altered to calcite, as testified by XRD) is very typical for an authigenic aragonite precursor (e.g. Aïssaoui, 1985; Savard et al., 1996; Mazzini et al., 2005). The precipitation of an aragonite precursor at seeps occurs in the shallow subsurface and in the presence of marine pore water with high sulfate

concentrations (e.g. Aloisi et al., 2002). Consequently, the precipitation of aragonite cements within cavities of the Paleocene seep carbonate at Fossildalen indicates precipitation in the presence of sulfate-rich pore water. At Recent seep sites marine water is often pumped into the sediment by seep biota, such as solemyid, thyasirid and vesicomid bivalves, which can influence the composition of pore fluids to the depth of several centimetres below the seafloor (e.g. Wallmann et al., 1997). Thyasirid bivalves, the representative of which (*Conchocele conradii*) is the most common fossil in Fossildalen seep carbonates, are among the most prolific bioirrigators in marine environments (e.g. Dufour and Felbeck, 2003; Dando et al., 2004), and the aragonite formation at this seep may indicate intensive reflux of marine water into the sediment due to thyasirid bioirrigation. The burrowing activity of seep organisms can further enhance the fluid circulation by creating conduits (e.g. Seike et al., 2012) which enhance the fluid release (e.g. Wiese et al., 2015), but also fluid reflux.

5.2. Paleocene wood-falls from the Basilika Formation

The characteristics of the wood-rich sandstone bed including i) the high degree of fragmentation and prevailing small size of the wood fragments, ii) deformation of the *Conchocele* specimens associated with the wood fragments, and iii) the association of the wood-rich sandstone with gravity flow derived deposits, suggest that the wood in the Basilika Formation was redeposited from its initial resting place (Kiel, 2008a; Kiel et al., 2009). The chaotic assembly of the *Conchocele* specimens and their deformation suggest that the thyasirids associated with the wood were also redeposited, although the transport was likely not far since all the specimens are articulated and the damage is restricted to fracturing and deformation. The small size of the wood chips from the sandstone seen in thin section could result from disintegration of the wood by gravity flow. The bed contains abundant pyrite, suggestive of reducing conditions in the wood-rich sediment. The large surface area of wood chips was likely a favourable substrate for the development of wood-degrading bacteria, which could have contributed to the formation of sulfide (e.g. Bienhold et al., 2013; Fagervold et al., 2014). In marine settings, decaying wood can generate sulfide, which usually attains higher concentrations only in the inner parts of the wood; the sulfide at the surface of the wood is present only occasionally (e.g. Yücel et al., 2013). However, wood chips mixed with muddy sediment would

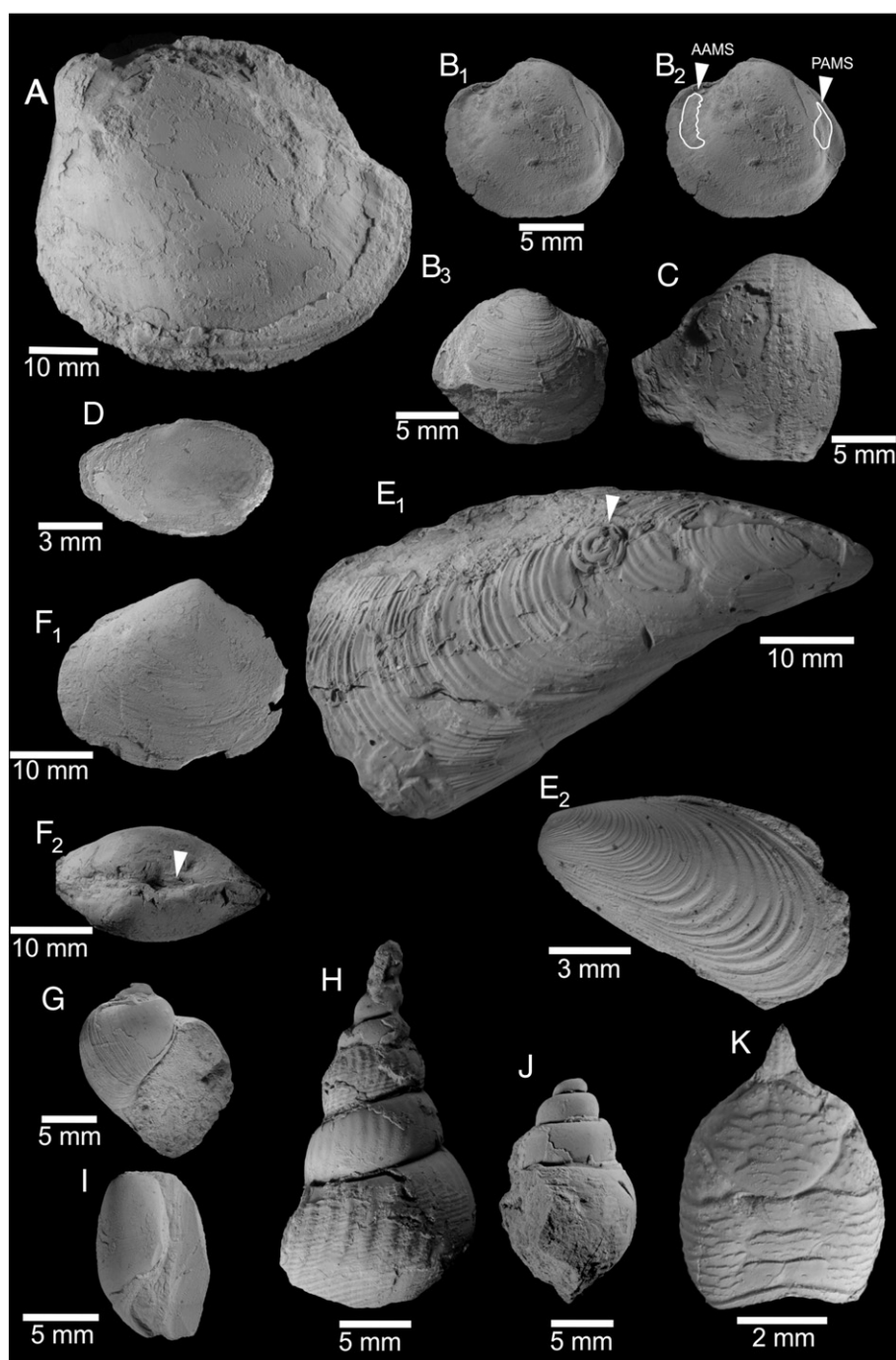


Fig. 12. Fossils from Fossiliden seep carbonates. A) *Conchocele conradii*, NRM-PZ Mo 182204; B) Myrteinae sp. B₁) left-lateral view of the internal mould, B₂) photo of the same specimen with anterior and posterior adductor muscle scars interpreted (AAMS and PAMS, respectively), B₃) right-lateral view of a partially preserved shell showing fine commarginal ornament, B₁–B₂ NRM-PZ Mo 182205, B₃ NRM-PZ Mo149145; C) Pholadoidea indet., NRM-PZ Mo149147; D) Protobranchia sp., GPIBo 152; E) *Inoperna?* sp. E₁) large curved specimen with commarginal ornament; the arrow marks a *Spirorbis* worm attached to the outer surface of the shell, E₂) a juvenile specimen, E₁ GPIBo 155, E₂ GPIBo 156; F) Astartidae? sp., F₁) right-lateral view of a damaged shell, F₂) anterodorsal view; the arrow points on the deep lunule; both photos NRM-PZ Mo149143; G) “naticiform” gastropod sp., GPIBo 112; H) Apporhaidae sp., GPIBo 117; I) Cylichnidae sp., GPIBo 115; J) Neogastropoda sp., NRM Mo149182; K) Munididae sp., GPIBo 85.

not have been influenced by the bottom waters and sulfide generated during their decay could have accumulated in their immediate surroundings. On the other hand, if the wood chips accumulated close to the surface of the sediment they could have inhibited gas exchange between the sediment and the overlying marine water, similar to the way xylophagous fecal pellets impede gas exchange in the sediment around modern infested wood logs (e.g. [Bienhold et al., 2013](#)). We speculate that in addition to wood, which is the main terrestrial plant material delivered to the sea ([West et al., 2011](#)), the investigated sandstone bed might have also included bark, twigs and leaves, which in modern

seas can cover the seabed close to areas rich in vegetation, even in relatively deep waters ([Wolff, 1979](#)), but are less likely to become fossilized. Such material may also have contributed to the overall substrate for the bacterial wood consumers around the Svalbard landmass during the Paleocene.

The characters found in the wood fragments found within the seep carbonates, including i) pervasive replacement of the wood tissue with seep carbonate, ii) infilling of the borings within the wood with seep carbonate, and iii) larger size of wood fragments from the seep carbonate compared to those from the sandstones, imply that the wood in

the seep carbonate was parautochthonous and was not moved far after it has reached the seabed. The wood fragments are up to dozens of cm long, which could be close to the original size of the fragments delivered to the seafloor (e.g. Wolff, 1979; Kiel, 2008a). The borings found within the wood in the seep carbonate are filled with the carbonate and bioclastic material, which could indicate that the wood was delivered to the seepage site either shortly after the borings were formed, or that the borings were formed directly at the seep site.

6. Discussion

6.1. *Conchocele* in Paleogene Boreal marine environments

The large Paleocene *Conchocele* specimens from the Basilika Formation carbonates from Fossildalen were initially identified as *Thyasira bisecta* by Hägg (1925) and subsequently described as the new species *T. conradii* by Rosenkrantz (1942). Its generic affiliation was later revised and placed into *Conchocele* by Rosenkrantz (1970). In Fossildalen, *C. conradii* forms mass accumulations in wood-rich beds and seep carbonates, however, the original collection of Vonderbank (1970) contains some similar articulated specimens with bright coarse-grained sandstone infillings, coming from apparently 'normal' marine deposits. The opinion that *C. conradii* is indeed a species of *Conchocele* is now acknowledged in the literature (e.g. Oliver and Frey, 2014) and was based on the occurrence of a very similar species from the lower Paleocene *Thyasira* Member of the Kangilia Formation, West Greenland, classified as *Conchocele* aff. *conradii* by Rosenkrantz (1942, 1970) and whose identity as a species of *Conchocele* has now also been confirmed (Amano et al., 2015b). In the *Thyasira* Member, *C. aff. conradii* is a common species associated with dark shales and sandstones rich in plant material, and with conspicuous fossiliferous carbonate concretions (Rosenkrantz, 1970). Smaller specimens (up to ca. 3 cm long) of *C. conradii* also occur in the upper Eocene–lower Oligocene Calypsostranda Group from Renardodden, Spitsbergen, Svalbard (Thiedig et al., 1979), which is a transitional shallow marine unit with abundant plant fossils and crustacean burrows (Dallmann, 1999). Therefore it seems likely that *C. conradii* and similar species were relatively common in the Paleogene of the Boreal Realm, and were often, although not exclusively, associated with seeps and sediments rich in plant material. Other species of *Conchocele* were also present in latest Cretaceous–Paleocene of Antarctica (Little et al., 2015); Cenozoic of the Circum-Pacific area (e.g. Krishtofovich, 1936; Amano et al., 2013; Hickman, 2015) and Neogene of Caribbean, especially Trinidad (e.g. Van Winkle, 1919; Gill et al., 2005; Kiel and Hansen, 2015). Recent *Conchocele* species are restricted to the Pacific (Kamenev et al., 2001; Okutani, 2002) and possibly the Caribbean (Gracia et al., 2012), and are unknown from the greater Atlantic (Oliver and Frey, 2014). The reason for this post-Paleogene restriction of the range of *Conchocele* is not yet clear.

6.2. Fossil hydrocarbon seepage on Spitsbergen

The available evidence shows that hydrocarbon seepage occurred on Spitsbergen at least twice during its geological history, and is still recorded in the waters around Svalbard today (e.g. Sahling et al., 2014). The first documented seepage episode took place during the Jurassic–Cretaceous transition in the Sassenfjorden area, approx. 25–30 km NE from Colesbukta (Hammer et al., 2011). The sediments document nearly 9 myr of seepage, contributing to formation of 15 carbonate bodies spread along a transect of approx. 20 km. The seepage there was dominated by methane of possible biogenic origin, as indicated by heavily depleted stable carbon isotopes of the carbonates ($\delta^{13}\text{C}$ values lower than -40% ; Hammer et al., 2011). Coeval seepage was also recorded ca. 80 km east of the Sassenfjorden area in Agardhbukta on Spitsbergen, where a single carbonate body of seep origin has been discovered (Vinn et al., 2014). Spitsbergen seepage during the Jurassic–Cretaceous transition time interval was probably not very intense, since all the

resulting seep carbonate bodies are of small size (Hryniewicz et al., 2015). The second episode of seepage is recorded by this study. Only *ex-situ* seep carbonates have been recorded in the current study, all of them in a very localized area around Fossildalen. It is likely, however, that Paleogene seepage on Spitsbergen was laterally more extensive, as indicated by the *Conchocele* occurrences in the carbonates west of Kapp Laila (Vonderbank, 1970), and following the fact that the Paleogene of Spitsbergen is not well studied palaeontologically. During the Paleocene, the seepage around Spitsbergen was largely based on methane, most likely biogenic, resulting in very negative carbonate and PMI carbon isotope values.

The majority of fossil seep sites are found at geotectonic settings similar where hydrocarbon seepage occurs today (Campbell, 2006). Fossil examples largely come from fossil forearc (e.g. Peckmann et al., 2002; Kuechler et al., 2012), rift (e.g. Gaillard et al., 1992; Kaim et al., 2013), and backarc basins (e.g. Amano et al., 2010). It is therefore intriguing that the Jurassic–Cretaceous seepage on Spitsbergen took place in a stable platform setting with very little tectonic activity (e.g. Dypvik et al., 1991). It is likely that Jurassic–Cretaceous gas release on Spitsbergen resulted from the accumulation of shallow gas within the organic-rich Agardhfjellet Formation hosting the Sassenfjorden seeps (Hryniewicz et al., 2015). A more dynamic tectonic setting has been proposed for the Paleogene of Spitsbergen. The Paleogene was the time of intracontinental strike-slip movement between Greenland and Barents Sea shelf, which peaked with the formation of Western Spitsbergen Orogenic Belt and Central Cenozoic Basin in its foreland during the Paleocene and the Eocene (e.g. Steel et al., 1981, 1985; Dypvik et al., 2011). It is therefore not impossible that some structural conduits, e.g. synsedimentary faults, were created in the area and provided migration pathways for the hydrocarbons during the Paleocene. Recent seepage along Western Spitsbergen takes place on a passive continental margin, a geotectonic environment with many Recent examples of known seepage (Campbell, 2006). Thus, although Jurassic–Cretaceous, Paleocene and Recent seepage episodes on and around Spitsbergen took place in a relative proximity, they occurred in different geotectonic settings.

6.3. Fossildalen seep and associated wood palaeoecology

The majority of the seep faunas, especially those formed in the deep water, contain only a limited number of macrofaunal species, the majority being specialists obligate to seeps (Kiel, 2010). Shallow water seeps, on the other hand, contain fairly diverse faunas where the great majority of species belong to background taxa, i.e. taxa present also in the surrounding 'normal' marine environment (Sahling et al., 2003; Dando, 2010). The moderate macrofaunal species richness (up to 17) of the Fossildalen seep fauna is more typical of moderately deep or even shallow water seeps (Kiel, 2010). The trophic structure, with only two chemosymbiotic bivalve species (*C. conradii* and a myrteine lucinid, if correctly identified as such), and only a single seep-restricted species (myrteine lucinid), with remaining species representing predators and scavengers (cylichnid and ?neogastropod, munidid crustaceans and possibly a "naticiform" gastropod), deposit-feeders (protobranch bivalves, aporrhaid gastropods), filter feeders (astartiid and mytilid, terebratulide brachiopod, *Spirorbis* sp.) and grazers (possibly "naticiform" gastropod), is also more indicative of a shallow water rather than a deep water seep. Nonetheless, the macrofaunal species diversity is still lower than in some well studied Mesozoic shallow water seep sites, for example the Late Cretaceous (Campanian) Tepee Buttes of the Western Interior Seaway, where up to 30 species per 'butte' have been recorded (e.g. Kauffman et al., 1996), or in some of the Jurassic–Cretaceous transition seeps from Sassenfjorden, where up to 32 species per seep have been documented (Hryniewicz et al., 2015). This could simply represent collection bias, as much less material has been found from the Fossildalen locality compared to the other two areas. Alternatively, it might reflect a slightly deeper water setting during the

Paleocene on Svalbard compared to the other two localities (e.g. Kiel, 2010), an effect of a general impoverishment of marine faunas in the early Paleogene (e.g. Roy, 1994) or oxygen depletion in the supposed stratified water column of the Spitsbergen Paleocene sea (e.g. Nagy et al., 2000). It is also likely that the lower diversity of the Fossildalen shallow water seep fauna, compared to other shallow water seep faunas, was caused by unstable environment with frequent gravity flows sweeping through the area of active seepage. Indications of this process are carbonate-filled specimens of *C. conradii* found within siltstones outside the seep area, and pockets of clastic material in the authigenic carbonate crusts found within these specimens. Gravity flows can be an important factor shaping seep environments, dispersing epifauna and effectively removing them from the seep ecosystem (e.g. Sandy et al., 2012), as well as covering the seafloor at the seep site with blankets of clastic material (e.g. Agirrezabal et al., 2013), thus sealing the carbonate and sulfidic substrate from seep-inhabiting biota. The latter factor could potentially have caused the small size of Fossildalen lucinids, which are much smaller than the majority of seep lucinids found elsewhere (Kiel, 2013). A very small size of Fossildalen lucinids as compared to *Conchocele* could result from different life habits of both bivalves; lucinids are deep burrowers (Taylor and Glover, 2010) which could not re-establish themselves as easily as a shallow burrowing *Conchocele* (Kharlamenko et al., 2016). With respect to size the Fossildalen lucinids are most similar to the shallow water lucinid assemblage from the Late Cretaceous (Cenomanian) Tropic Shale seeps carbonates from the Western Interior Seaway, USA (Kiel et al., 2012). The small size of Tropic Shale seep lucinids might have resulted from frequent gas explosions and toxic conditions, killing the lucinids before they could fully grow (S. Kiel, 2016, personal communication). This scenario is less probable for the Fossildalen site, however, since gas eruptions should have caused the *Conchocele* specimens to be similarly small, and this is not what is observed.

Plant material, including sunken wood, constitutes an important source of organic carbon delivered to the deep sea (e.g. Wolff, 1979; Pailleret et al., 2007; Bernardino et al., 2010). The most obvious traces of macrofaunal utilization of plant remains at Fossildalen are borings in the wood fragments from the seep carbonates (Fig. 8B). The most significant modern marine wood-borers are teredinid (Turner, 1966; Nair and Saraswathy, 1971) and xylophagid bivalves (e.g. Knudsen, 1961; Voight, 2007), chelurid amphipods (Barnard, 1959) and limnoriid isopod crustaceans (Borges et al., 2014). Some sipunculids have also been suggested to be able to bore into submerged wood (Wolff, 1979; Rice, 1985). Terebinids are especially widespread in the tropical shallow waters and are most efficient in colonising floating wood (Nair and Saraswathy, 1971). Their borings are elongated and aligned along the wood grains, with walls covered with calcareous linings (Turner, 1966). The shells of the wood-boring bivalve (Fig. 11C) and borings found in the wood from Fossildalen are well within the size range of teredinids; however, the borings lack calcareous linings. This absence is not necessarily definitive for the identification of these borings, as the calcareous linings produced by teredinids can be very thin and fragile (Turner, 1966), which leaves them prone to dissolution, damage and destruction. In contrast to teredinids, modern xylophagids colonise sunken wood on the seafloor and are most common in the deep sea (Knudsen, 1961), although they are not exclusive to this environment (Santhakumaran, 1980). The great majority of xylophagids do not exceed 10 mm in diameter (Knudsen, 1961) and the borings observed in this study are nearly twice the diameter of xylophagid borings. The Fossildalen wood borings also lack fecal chimneys characteristic of xylophagid borings, i.e. wood-rich fecal linings of the inner walls of the borings (Kiel et al., 2009). However, as for the lack calcareous linings, the lack of fecal chimneys is not conclusive and could simply be a preservation issue, with a loss of fecal chimneys due to taphonomy. Some of the Fossildalen wood borings could theoretically have been formed by sipunculids, as they have an appropriate size and lack calcareous linings (Rice, 1985). We speculate that some of the invertebrates

found in the Fossildalen seep carbonates (munidid crustaceans, mytilid bivalves, naticiform gastropods) could have been attracted to the seep site by the food, shelter and substrate provided by the sunken wood (Wolff, 1979). However, the Fossildalen fauna does not contain any species typically associated with deep-water sunken driftwood of similar age (Kiel and Goedert, 2006; Kiel, 2008a; Kiel et al., 2009). It is likely that the Paleocene shallow-marine benthic food-web in Fossildalen was to some extent based on terrestrial plant litter and microbial processes associated with its decomposition (e.g. McLeod et al., 2010). However, the absolute influence of wood on the faunal community of Fossildalen seep carbonates is at the moment difficult to ascertain.

6.4. Macroevolutionary considerations

The Fossildalen seep fauna is dominated by the large thyasirid *Conchocele conradii*. Thyasirids are known from seeps since the Early Cretaceous (Berriasian) (Hryniewicz et al., 2014). However, in a great majority of fossil seep sites they are rather uncommon (Kiel, 2010). An exception to this is a number of latest Cretaceous–earliest Paleogene seeps where large thyasirids occur in large numbers and often dominate the macrofaunal assemblage. The Sada Limestone (Campanian–Maastrichtian) from Shikoku, Japan (Nobuhara et al., 2008), contains mass accumulations of the large thyasirid *Aphrodina hataii* (Katto and Hattori, 1965), exceeding 90 mm in length (K. Hryniewicz, personal data). This species co-occurs with very rare lucinid and solemyid bivalves, worm tubes and a species of gastropod of as yet uncertain taxonomic affinity (S. Kiel, 2015, personal communication). Other examples are the Maastrichtian seeps from the James Ross Basin, Antarctica, with numerous specimens of *Thyasiria townsendi* (very likely a species of *Conchocele*). These co-occur on Seymour Island with solemyid and lucinid bivalves, and various gastropods (Little et al., 2015). The Paleocene Fossildalen site constitutes the third example from the relatively short latest Cretaceous–earliest Paleogene time interval where exceptionally large thyasirids occur frequently at seeps. This is even more striking considering that only two other seep sites from this time interval are known: Maastrichtian seeps from the Western Interior Seaway, USA (Metz, 2010) and the Paleocene Panoche Hills seeps from California, USA (Schwartz et al., 2003). The dominance of large thyasirids of seep faunas during the latest Cretaceous to earliest Paleogene is puzzling. It could perhaps be explained by a lower global sea level (Haq et al., 1987; Van Sickle et al., 2004) and global cooling at that time (Linnert et al., 2014). Shallower latest Cretaceous–earliest Paleogene seas could have been more favourable to *Conchocele*, which today seems to prefer shelf to middle bathyal water depths (Kamenev et al., 2001; Okutani, 2002). Another explanation might be that thyasirids, including *Conchocele*, seem to favour temperate to cold waters (Taylor and Glover, 2010). For bivalves, water temperature is especially significant during spawning (e.g. Fujiwara et al., 1998), and cooler latest Cretaceous and earliest Paleogene oceans might have promoted more efficient dispersal of thyasirids.

Molluscs, such as paskentid, provannid and hokkaidoconchid gastropods, the large kalenterid bivalve *Caspiconcha*, and bathymodiolin mussels and vesicomid clams (Squires and Gring, 1996; Kelly et al., 2000; Amano and Kiel, 2007; Kiel, 2008b; Kiel et al., 2008; Kiel and Amano, 2013; Jenkins et al., 2013; Kaim et al., 2014), typically associated with Mesozoic and Cenozoic hydrocarbon seep carbonates have not yet been found at the Fossildalen site. The absence of paskentid gastropods could simply be an age issue, as their currently known range is from the Late Jurassic (Oxfordian) to the Late Cretaceous (Turonian; Kaim et al., 2014). The same applies to *Caspiconcha*, which is most common in latest Jurassic (Tithonian) to Early Cretaceous seeps, with the last known seep occurrence in the Late Cretaceous (Campanian; Jenkins et al., 2013). Hokkaidoconchid gastropods range from the Late Jurassic (Oxfordian) to the Eocene (Kiel and Hansen, 2015), and therefore could potentially have occurred in the Fossildalen seep site. This also goes for the provannid gastropods, which are known from the

Late Cretaceous (Cenomanian) onwards (Kaim et al., 2008). The absence of both groups from the Fossildalen seep carbonates could therefore be a function of more local, ecological factors. Both vesicomyids and bathymodiolins appear at seeps from the mid-Eocene (Amano and Kiel, 2007; Kiel and Amano, 2013), therefore their absence from the Fossildalen site could also be related to age. The appearance of both vesicomyid and bathymodiolin bivalves in the Eocene was explained by a rapid repopulation of deep-marine chemosynthesis-based settings after a putative extinction event caused by oceanic anoxia during the Paleocene-Eocene Thermal Maximum (Vrijenhoek, 2013), or, instead, by an increase of seawater sulfate concentrations in the Eocene (Kiel, 2015). The absence of bathymodiolins and vesicomyids from the Paleocene Fossildalen seep corroborates the observation that the radiation of bathymodiolins and vesicomyids took place in the Eocene. Caution is needed here because the shallow water setting of Fossildalen seep site might not have been a favourable environment for bathymodiolins and vesicomyids.

7. Conclusion

The available evidence, including petrography, carbon isotope signatures of the carbonate approaching $\delta^{13}\text{C}$ value of -50% V-PDB, and the archaeal biomarker having $\delta^{13}\text{C}$ value of ca. -100% V-PDB, is consistent with the interpretation of the carbonates from the Basilika Formation in Fossildalen, Spitsbergen, Svalbard, as an ancient hydrocarbon seep deposit. The moderately diverse fauna associated with the Fossildalen carbonates consists of molluscs with subordinate crustaceans, polychaetes and brachiopods, and wood, some of which has bivalve borings. The most common mollusc is a species of the large thyasirid bivalve genus *Conchocele*, which was much more broadly distributed during the latest Cretaceous–Paleocene time period than it is now. The seep fauna is associated with a wood-rich sandstone bed also containing *Conchocele* specimens. Apart from *Conchocele*, the seep fauna does not contain any species which is typically associated with contemporary seeps. Together with the moderate diversity of the fauna, we interpret the faunal composition as typical of relatively shallow water setting for the Fossildalen seep. No bathymodiolin and vesicomyid molluscs have been found in the fauna, which corroborates the observation that both bivalve groups radiated into seep environments after the Paleocene.

Acknowledgments

We would like to thank Grażyna and Marian Dziewiński (Institute of Paleobiology, Warszawa) for photography of the fossils, Adam Zaremba for preparation of the polished slabs, Salahaddin Akhavan (Natural History Museum, Oslo) and Zbigniew Strąk (Institute of Paleobiology, Warszawa) for preparation of the thin sections. We would also like to thank Akiko Goto and Takashi Hasegawa (both Kanazawa University, Japan) for biomarker and isotope analyses. We would like to sincerely thank Kristin Jæger Wexhal (Longyearbyen) for assistance and protection during field work, and Norsk Polarinstitutt staff for assistance and equipment preparation during our fieldwork. The funding for this project was provided by the Polish National Science Centre (NCN) research grant no. 2014/15/B/ST10/04886 entitled 'The influence of Paleocene/Eocene Thermal Maximum on oceanic chemosynthesis-based ecosystems'. The fieldwork on Svalbard and the research was registered in the Research in Svalbard database under a number RiS 10173 'The influence of Paleocene/Eocene Thermal Maximum on oceanic chemosynthesis-based ecosystems'. This paper benefited from the careful reviews of an anonymous referee and Steffen Kiel, whom we would like to thank.

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