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Paleocene chemosynthesis-based marine communities from Spitsbergen, Svalbard

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Abstract

A recently discovered Paleocene seep locality from Fossildalen on Spitsbergen, Svalbard, is described. This is one of a very few seep communities of the latest Cretaceous–earliest Palaeogene age, and the best preserved Paleocene seep community known so far. The seep

carbonates and associated fossils have been first identified in museum collections, and subsequently sampled in the field. The carbonates are exclusively ex-situ and come from the offshore siltstones of the Basilika Formation. 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 lipid are consistent with the formation at fossil hydrocarbon seep. The invertebrate fauna associated with the carbonates is of moderate diversity (16 species) and has a shallow water affinity. It contains a species of the thyasirid genus *Conchocele*, common in other seeps of that age. The finding sheds new light onto the history of seepage on Svalbard, and onto the evolution and ecology of seep faunas during the latest Cretaceous–earliest Palaeogene time interval.

Keywords: Carbonates, chemosynthesis-based communities, *Conchocele*, ecology, hydrocarbon seeps, Paleocene, Svalbard

1. Introduction

Hydrocarbon seeps are sites of submarine hydrocarbon emission, common in shallow to deep marine settings in virtually all oceans (e.g. Hovland, 1992; Fujikura et al., 1999; Domack et al., 2005; Dando, 2010). High concentration of reduced compounds causes seeps to host dense communities of invertebrates relying on chemosynthetic primary production, unlike the 'normal' marine benthic faunas which in great majority depend on organic matter produced due to 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 bulk of the

oceanic chemosynthesis-based communities consists of solemyid, lucinid, thyasirid and vesicomylid clams, bathymodiolin mussels, abyssochryssoid 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), the modern composition of seep communities is not ancient and has been established in the Palaeogene (Little and Vrijenhoek, 2003; Kiel and Little, 2006; Vrijenhoek, 2013; Kiel and Amano, 2013; Kiel, 2015; Kiel and Hansen, 2015). The fossil sites from the latest Cretaceous and the earliest Palaeogene are therefore very important for understanding the formation and origin of modern seep faunas. There is, however, just a handful of sites from this time interval, including some of the Tepee Buttes from the Maastrichtian of the Western Interior Seaway, USA (Metz, 2010); 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 Paleocene Panoche Hills seeps from California, USA (Schwartz et al., 2003). Possible chemosynthesis-dependent communities associated with sunken driftwood have also been described from the Paleocene of Hokkaido (Amano and Jenkins, 2014; Amano et al., 2015a, b). This paper describes carbonates and wood-fall occurrences and associated invertebrate faunas from the Paleocene marine sediments from Fossildalen, Spitsbergen, Svalbard. The fauna from carbonates is of moderate diversity and is dominated by the large thyasirid bivalve *Conchocele conradi* Rosenkrantz, 1942, with subordinate protobranch and lucinid bivalves, naticiform gastropods and other invertebrates. We present the petrographic and geochemical evidence supporting our interpretation of the carbonates as a fossil hydrocarbon seep deposits, and discuss the

geological, ecological and evolutionary significance of the associated 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 Palaeogene 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 metres 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 carbonates and associated fossils described in this paper come from the late Paleocene Basilika Formation (Major and Nagy, 1972; Manum and Throndsen, 1986; Dallmann, 1999). The formation represents offshore siltstones and subordinate sandstones up to 350 m in thickness with several thin volcanogenic clay layers (Dypvik and Nagy, 1978). The benthic foraminiferal fauna of the Basilika Formation indicates restricted marine conditions and oxygen depletion, possibly related to the water column stratification (Nagy et al., 2000). The formation contains numerous glendonites – pseudomorphoses after carbonate hexahydrate mineral ikaite (Suess et al., 1982), indicative of cold-water conditions at Spitsbergen during the Paleocene (Spielhagen and Tripathi, 2009).

3. Materials and methods

3.1. Locality information

The carbonates and associated invertebrate fossils treated in this paper were previously described by Hägg (1927), Gripp (1927) and Vonderbank (1970). Chronologically the first work dealing with carbonates and associated fossils from the Paleocene of Fossildalen is that of Hägg (1927). The carbonate samples and associated fossils he described are stored at Naturhistoriska Riksmuseet, Stockholm, Sweden. They were collected at Colesbukta on the southern coast of Isfjorden by the Norwegian mining engineer Arthur Lewin during the summers of 1923 and 1924. The samples were the following winter handed over to Hägg, whose locality description is thus second-hand and rather general, indicating the western side of Colesbukta, 150 meters above sea level and about 300–400 meters above the base of the Cenozoic. The hand-drawn map of Arthur Lewin stored in Stockholm together with the appearance of the material suggest that the 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 invaluable for the site identification as he participated in the German 1925 Spitsbergen Expedition and collected the material himself. Gripp states that the expedition learned from Hägg about Arthur Lewin's discovery a few years before and visited the same locality on western side of Colesbukta. The site was in a mid-section of a valley with a house close to the mouth 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 has collected at the same site as Lewin and

Gripp. It can be added that Gripp's expedition failed to locate 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 the fossiliferous carbonates of Hägg (1927) and Gripp (1927) in Fossildalen. The carbonates are exclusively ex-situ. They occur as 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. The great majority of the samples were found in the riverbed of the small creek flowing in Fossildalen (Fig. 1); a few weathered carbonate-filled fossils have also been found in the debris, approx. 50 m east from the creek. No carbonates have been found in situ. We found an in situ sandstone bed with abundant wood debris and Conchocele cropping out along the western side of the valley, approximately 12 meters above the riverbed at the position of 78° 5'52.68" E, 14°31'51"59 E. Fragments of those 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 sample has been tested for the presence of palynomorphs. 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 (ZnCl_2) was then used to separate any remaining mineral particles from the organic material.

To extract agglutinated foraminiferal fossils, a two-kilograms 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 the fractions (three fractions) between 63 and 500 μm were collected and dried. Acetic acid was used in case the sample also contained any vertebrate remains like fish teeth or scales, but none were found in the relevant fractions.

3.3. Petrography

A set of uncovered thin sections (48 mm x 28 mm) was prepared in order to identify the main carbonate phases of the carbonate, and to interpret their spatial and temporal relationships. Polished slabs have also been prepared and used to interpret the temporal and spatial relationship between the carbonate and the surrounding siliciclastic rock. Thin sections and polished slabs have been also prepared from sunken wood-rich sandstone. The thin sections from all lithologies were subsequently examined in normal and cross-polarized light under the optical microscope and photographed with the digital camera. The terminology of carbonate 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 phase were performed by Ultima IV(Rigaku) at the Kanazawa University, Kanazawa, Japan.

3.4. Stable carbonate carbon and oxygen isotopes

Samples for stable carbonate carbon and oxygen isotope analyses of the carbonate were hand from different phases to produce powders, or mechanically crushed using pliers, and afterwards analysed by Thermo Scientific Finnigan GasBench II/ Isotope ratio mass spectrometry (IRMS: Delta V Advantage) at the Kanazawa University, Kanazawa, Japan. Measured values were corrected using two points calibration with NBS19 and LSVEC. The standard deviations (1σ) of replicate analyses of NBS19, LSVEC and 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 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 × 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 (C₁₇, C₁₈, C₂₀, C₂₄, C₂₈, and C₃₂) with known isotopic compositions before analyzing the sample.

4. Results.

4.1. Age of the deposits

The palynological material 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. These are: *Cerodinium dartmoorium*, *Cerodinium striatum*, *Oligosphaeridium* complex, *Paleoperidinium pyrophorum* and *Spiniferites ramosus* (Fig. 3). Such composition of the

dinoflagellate assemblage allows to precisely date the sample. The taxa that define the stratigraphic position are: *Cerodinium dartmoorium*, *Cerodinium striatum* and *Paleoperidinium pyrophorum*. The co-occurrence interval for these species is the upper Paleocene (Thanetian), the upper part of the D3 and the lower part of D4 dinoflagellate cyst biozones (Fig. 4; Costa and Manum, 1988). The assemblage is very similar to that previously described from the same locality (Manum and Thronksen, 1986; fig. 4, p. 113) however these authors suggested the interval 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 D4 (Powell, 1992) and the appearance of *C. dartmoorium* in the upper D3 (the lower/upper Paleocene boundary in Manum and Thronksen, 1986).

The preservation of the foraminiferal specimens is mostly excellent, owing to the authigenic precipitation of the carbonates, as observed in other fossil seeps in Spitsbergen (Hjálmarasdóttir et al., 2012). Of 485 specimens picked for micropalaeontological analysis, 28 taxa are identified in the sample. Five of these are stratigraphically important; *Haplophragmoides porrectus*, *Haplophragmoides walteri*, *Reticulophragmoides jarvisi*, *Verneuilinoides subeocaenus*, and *Marssonella oxycona* (Fig. 4). The assemblage is entirely agglutinated with medium diversity. Dominating species are *Haplophragmoides* sp. and *Labrospira turbida*. These species indicate that the sample is of late Paleocene–early Eocene age (Charnock and Jones, 1990).

A stratigraphic atlas of foraminifera by King (1989) compares microfaunal marker events in the Paleocene North Sea to the dinoflagellate zones established by Costa and Manum (1988), and which are referred to in the present study. The foraminiferal assemblage is most consistent with biozone NSB2. As previously stated, the palynological material

indicates biozones D3–D4 (late Paleocene), and it is established that the sampled formation is Basilika Formation. Thus it is indicated that the biozonation by King (1989) for foraminifera is not applicable in this locality on Spitsbergen.

4.2. Petrography of the carbonates

Fossildalen carbonates occur exclusively ex-situ as decimetre-sized carbonate blocks, and as 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 Conchocele occurring in the sandstone blocks (Fig. 5C). Cavities within carbonates are rare and are either located within geopetal structures within Conchocele (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). It is followed by the authigenic carbonate crust, composed of a discontinuous layer of yellow calcite (yc; Fig. 5E) and botryoidal calcite (bc) (Fig. 5F). The particular crystallites forming botryoids are fibrous and elongated, and have feather-like culminations (Fig. 5F) and contain inclusion-rich bands.

The carbonate crust lining geopetal structures within Conchocele extracted from the siltstone blocks is sometimes fractured and separated from the shell (sh), with the fractures sealed by translucent microspar (ms, Fig. 6A). 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 translucent microspar from Conchocele extracted 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 Conchocele is equant calcite spar (eq; Fig. 6F).

The inner walls of the cavities from within carbonate blocks are lined with carbonate crust similar to that from the geopetal structures in Conchocele. A phase post-dating the formation of the authigenic carbonate crust 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 (Fig. 7A). Some carbonate blocks contain a lot of sunken 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 worm tubes. When it's possible to observe, the borings are oriented parallel to the grain of the wood.

4.3. Stable carbon and oxygen isotopes of carbonates

Stable carbon and isotope composition of Fossildalen carbonates is given in Table 1 and on Fig. 9. Micrite is heavily depleted in ^{13}C , with $\delta^{13}\text{C}$ values varying between -38.8 and -49.4‰. Botryoidal carbonate has similar to slightly higher $\delta^{13}\text{C}$ values as the micrite, varying between -32.5 and -42.9 ‰. 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 euhedral carbonate filling some voids is less depleted with respect to 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 with respect to heavy oxygen isotope ($\delta^{18}\text{O}$ of -17.7‰). The shell samples of large thyasirid bivalves 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 Fossildalen carbonates is shown in Fig. 10. Predominant hydrocarbons in the sample 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 sunken-wood bearing sandstone bed

The sunken wood-bearing sandstone bed is fine-to medium grained, composed predominantly of quartz with fine admixture of chert fragments (Fig. 11A). The outer surface of the blocks is covered with rusty crust, whereas the 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 can constitute up to 50% of the total pore space available. The sandstone is mostly devoid of carbonate, 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. Vast majority of them are unidentified fragments and chips a few mm in diameter. The inner structure of those small chips is well preserved and it is possible to distinguish between particular wood cells (Fig. 11C). The outer surface of the wood chips is usually heavily worn and covered with pyrite crust (Fig. 11D). Larger fragments of the wood are rare and altered beyond identification, often being heavily weathered and crumbling when touched in the field.

4.6. Fossil content

The Fossildalen carbonates and sunken wood-rich sandstone bed contain macrofossil assemblage of high diversity and abundance, composed predominantly of molluscs with subordinate crustaceans, brachiopods and worm tubes. The fossils from Fossildalen carbonates were previously identified and figured by Hägg (1927), Gripp (1927) and Vonderbank (1970) and we present the original identifications with the source indicated and with our re-interpretations in Table 2. Taxonomic work on the material is currently ongoing.

The fauna is heavily dominated by bivalves. Gastropods, crustaceans and worm tubes are less abundant but locally common; brachiopods are accessory and only few specimens have been found (Table 2). The dominant bivalve is a large thyasirid *Conchocele conradi*, occurring in mass-accumulations of specimens up to 85 mm long (Fig. 12A). The species occurs also in the surrounding grey siltstones; those specimens have carbonate filling, their shells are sometimes damaged, and the surrounding mudstones exhibit flow structures and deformations characteristic for turbidite deposits. *Conchocele conradi* is the only macrofaunal fossil found in the sunken wood-rich sandstone, where virtually all specimens are deformed and fractured. A somehow less common bivalve from carbonates is a small (up to 16.5 mm

long) heterodont species, which Vonderbank (1970) classified as a species of a lucinid *Anodontia* (Fig. 12B). This species has elongated anterior adductor muscle scar which could indicate a lucinid, and a weakly oval shape and fine commarginal growth lines reminiscent of myrtein lucinids from deep-water seeps (Kiel, 2013); for now we restrain from its generic identification. We were able to find a single specimen of a wood boring pholadoid bivalve species, either xylophagain or teredinid (Fig. 12C); more shells which could represent this species are visible on cross sections of some borings. Fairly common bivalves are elongated protobranches, probably nuculanids, malletiids and yoldiids (Fig. 12D). Less common bivalve is a species of a mussel (Fig. 12E). This species is elongated and has a pointed umbo, thus it does not resemble a typical seep bathymodiolin mussel and is more similar to shallow marine *Mytilus*. 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 classifying it into this genus. The elongated species of a heterodont bivalve identified as a species of *Astarte* by Hägg (1927) and Gripp (1927) has an elongated shell and a sunken lunule (Fig. 12F) which is common among some astartiids and we tentatively classify this species as an astartiid.

The gastropods, four species of which have been identified, are generally less common in the material than the bivalves. The most abundant gastropod species is a low-spined naticiform gastropod interpreted by Vonderbank (1970) as a species of *Ampullonatica* (Fig. 12G). This species occurs in carbonate samples which are rich in sunken driftwood, often directly on the wood. We tentatively interpret it as a naticiform gastropod due to lack of evidence allowing for more precise identification. Other gastropods occur much more seldom 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 more detailed identification was not possible. Other gastropods include a cylichnid (Fig. 12I) and a possible neogastropod (Fig. 12J).

Carbonate samples rich in sunken driftwood, 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 ascribed to a new galatheid decapod species *Galathea spitzbergica*. We agree the fossils are of galatheoid origin, although the ornament of the carapace, especially dorsally-ridged rostrum suggest the species belongs to munidids rather than to galatheids (Ahyong et al., 2010). Brachiopods are represented by a single terebratulide species, assigned by Gripp (1927) to *Terebratulina* sp. The preliminary examinations of our material suggest that brachiopods belong to a short-looped terebratulid rather than a long-looped terebratellid, as indicated the lack of dorsal septum; the character of beak and foramen and smooth shell surface exclude the genus *Terebratulina*. The remaining macrofossil species is *Spirorbis* worm tube (Vinn et al., 2013), attached to the surface of large mytilid (Fig. 12E). In addition, wood rich carbonates contain numerous agglutinated tubes up to 3 mm in diameter. Microfossils comprise agglutinated foraminifera and ostracods.

5. Interpretation

5.1. Paleocene hydrocarbon-seep carbonates from the Basilika Formation

The available evidence, including the observed textures and heavily depleted $\delta^{13}\text{C}$ composition of carbonates and the lipid biomarker PMI, are consistent with the 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 are formed mostly by the carbonate authigenesis within background muds and sands related to the anaerobic oxidation of methane at fossil seep site (AOM; Boetius et al., 2000). The presence of highly ^{13}C -depleted PMI (ca. -100‰) in the sample indicates existence of anaerobic methane-oxidizing archaea (Peckmann and Thiel, 2004). The archaea are responsible for the AOM with sulphate-reducing bacteria. The very low $\delta^{13}\text{C}$ values of investigated carbonates approaching -50‰ and that of PMI as low as -100‰ indicate that biogenic methane was a 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 carbonate micrites may have formed prior to the botryoidal carbonates. On average, the micrites of Fossildalen seep carbonates are more ^{13}C -depleted than the botryoidal cements, which may indicate that both phases formed in a partially closed system. The $\delta^{18}\text{O}$ values of the Fossildalen carbonates in great majority oscillate between -3.7 and -6.2‰ , and partially overlap with those of the glendonites common in 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 taken into consideration. Indeed, the carbonate cements 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‰) is likely related to freshwater reflux through the formation (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 Palaeogene 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 carbonate in the Paleocene Fossildalen seep. Consequently, rare cavities within micrite and geopetal structures within thyasirid 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 crust was most likely mobilized during the 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 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 the yellow aragonite precursor, precipitated in the immediate vicinity of the methanotrophic consortia participating in AOM (Hagemann et al., 2012). 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) are very typical for authigenic aragonite precursor (e.g. Aïssaoui, 1985; Savard et al., 1996; Mazzini et al., 2005). The precipitation of aragonite precursor at seeps is associated with shallow subsurface and presence of marine pore water with high sulphate concentrations (e.g. Aloisi et al., 2004). Consequently, the precipitation of aragonite cements within cavities of the Paleocene seep carbonate on the Svalbard site indicates precipitation in the presence of sulphate-rich pore water. At Recent seep sites the 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 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 on one hand (e.g. Wiese et al., 2015), but also fluid reflux on the other.

5.2. Paleocene woodfalls from the Basilika Formation

A set of characters of the sunken wood-bearing sandstone bed like i) high degree of fragmentation and prevailing small size of the wood fragments, ii) deformation of fossils associated with the wood fragments, iii) association of the wood-bearing sandstone with

turbidite beds, suggest that the sunken driftwood is redeposited from its initial resting place (Kiel, 2008a; Kiel et al., 2009). The chaotic assembly of the shells and their deformations suggest that thyasirids associated with the wood are also redeposited, although the transport was likely not very long as all the fossils are articulated and the damage is restricted to fracturing and deformations, without defragmentation and disarticulation. The small size of the wood chips from the sandstone could result from defragmentation of the sunken driftwood by turbidity currents. 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 contribute to the formation of sulphide (e.g. Bienhold et al., 2013; Fagervold et al., 2014). In marine settings, decaying wood can generate sulphide which usually attains higher concentrations only in the inner parts of the wood; the sulphide at the surface of the wood is present only occasionally (e.g. Yücel et al., 2013). However, wood chips mixed with muddy sediment would not be influenced by the bottom waters and sulphide generated during their decay could accumulate in their immediate surroundings. On the other hand, if wood chips accumulated close to the surface of the sediment they could inhibit the gas exchange between the sediment and the overlying marine water similar to the manner xylophagous fecal pellets impeded gas exchange in the sediment around infested wood logs (e.g. Bienhold et al., 2013). We also speculate that in addition to wood, which is the main terrestrial plant material delivered to the sea (West et al., 2011), investigated sandstone bed could initially comprise bark, twigs and leaves which in modern seas can cover the seabed close to the areas rich in vegetation even in relatively deep waters (Wolff, 1979), but are less likely to become fossilized. Such material could also contribute to the overall substrate for the bacterial wood consumers during the Paleocene on Svalbard.

The features exhibited by the wood fragments found within the seep carbonates like i) strong replacement of the wood tissue with seep carbonate ii) filling of the borings within the wood with seep carbonate and iii) larger size of the wood fragments from the seep carbonate as compared to those from the sandstones, imply that wood in the seep carbonate is parautochthonous and has not been redeposited much since 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 sea bottom (e.g. Wolff, 1979; Kiel, 2008a). The borings found within the wood excavated from the seep carbonate are filled with the carbonate and bioclastic material, which could indicate that the wood has been delivered to the seep site either shortly after the borings were formed, or that the borings were formed directly at the seep site. It is likely that the wood has been delivered to the seep site just after it sank, or was redeposited to the seep after a very short residence on the seabed.

6. Discussion

6.1. Conchocele in Palaeogene Boreal marine environments

Large Paleocene thyasirids (up to 85 mm in length) from the carbonates of the Basilika Formation of Svalbard were initially classified as *Thyasira bisecta* (Hägg 1927). The Svalbard Paleocene thyasirid was subsequently separated into new species *Th. conradi* by Rosenkrantz (1942). The generic affiliation of this species was later revised, and it was assigned to *Conchocele* (Rosenkrantz, 1970). On Spitsbergen, *C. conradi* forms mass accumulations in sunken driftwood-rich beds and seep carbonates, which is its most common mode of occurrence. However, the original collection of Vonderbank (1970) contains some specimens with bright coarse-grained sandstone filling, coming apparently from 'normal' marine

deposits. The opinion that the Spitsbergen Paleocene thyasirid is a species of *Conchocele* is now acknowledged in the literature (e.g. Oliver and Frey, 2014) and was initially based on very similar species from the early Paleocene Thyasira Member of the Kangilia Formation, West Greenland, which was classified as *Conchocele* aff. *conradi* (Rosenkrantz, 1942, 1970) and which identity as a species of *Conchocele* is now confirmed (Amano et al., 2015b). In Thyasira Member, *C.* aff. *conradi* 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 *Conchocele conradi* occur also in late Eocene–early 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). It therefore seems that *Conchocele conradi* and similar species were relatively common in the Palaeogene of the Boreal Realm, and associated with seeps and sediments rich in plant material, although not exclusive to them. Other species of *Conchocele* were also present in latest Cretaceous–Paleocene of Antarctica (Little et al., 2015) and Cenozoic of Circum-Pacific area (e.g. Kristofovich, 1936; Amano et al., 2013; Hickman 2015). Recent *Conchocele* is restricted to Pacific (Kamenev et al., 2001; Okutani 2002) and possibly Caribbean (Gracia et al., 2012) and is unknown from the Atlantic (Oliver and Frey, 2014). The reason of this post-Palaeogene restriction of the range of *Conchocele* is yet unclear.

6.2. Fossil hydrocarbon seepage on Spitsbergen

The available evidence shows that hydrocarbon seepage occurred on Spitsbergen at least twice during its geological history. The first documented seepage episode took place during the Jurassic–Cretaceous transition around Sassenfjorden area, approx. 25–30 km NE from

Colesbukta (Hammer et al., 2011). The sediments there document nearly 9 Ma 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 isotope of the carbonates ($\delta^{13}\text{C}$ values lower than -40‰; Hammer et al., 2011). Coeval seepage is also recorded ca. 80 km east from Sassenfjorden area in Agardhbukta on Spitsbergen, where a single carbonate body of seep origin has been discovered (Vinn et al., 2014). Spitsbergen seepage at that time was probably not very intense, since all 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 remains of one or more carbonate bodies have been recorded in the current study, all of them on a very localized area around Fossildalen. It is likely, however, that Palaeogene seepage on Spitsbergen was laterally more extensive, as Palaeogene of Spitsbergen is generally poorly recognized palaeontologically. During the Paleocene, the seepage was largely based on methane, most likely biogenic with resulting stable carbon isotope composition of the carbonates approaching -50‰ and the archaeal biomarker PMI, ca. -100‰.

The majority of the fossil seep sites is found within geotectonic settings similar to settings where such environments appear today (Campbell, 2006). Those comprise mostly 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 recorded (e.g. Dypvik et al., 1991). It is likely that Jurassic–Cretaceous gas release on Spitsbergen was manifestation of accumulation of shallow gas within the organic-rich Agardhfjellet Formation hosting the Sassenfjorden seeps (Hryniewicz et al., 2015). More labile tectonic setting has been proposed for the Palaeogene

of Spitsbergen. The Palaeogene 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 have been created in the area and provided migration pathways for the hydrocarbons. Thus, although both Jurassic–Cretaceous and Paleocene seepage episodes on Spitsbergen took place in a relative proximity, they were formed in different geotectonic settings.

6.3. Ecology of Fossildalen seep and associated sunken driftwood

The majority of the seep faunas, especially those formed in the deep water, contains only a limited number of macrofaunal species, the majority of them being specialists unique for seeps (Kiel, 2010). Shallow water seeps, on the other hand, contain fairly diverse faunas where the great majority of species belongs to the background taxa, i.e. taxa present also in the surrounding ‘normal’ marine environment (Sahling et al., 2003; Dando, 2010).

Analogically, the relatively high macrofaunal species richness (up to 16) of 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. conradi* and a myrtein lucinid), and only a single seep-restricted species (myrtein 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 sp., terebratulide brachiopod sp., *Spirorbis* sp.) and grazers (possibly naticiform gastropod) is also more indicative of shallow water setting rather than of deep water environment. Nonetheless, the macrofaunal species diversity

is still lower than in some well studied Mesozoic shallow water seep sites, for example in Late Cretaceous (Campanian) Tepee Buttes in 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 a collection bias, as Fossildalen seep has not been studied as extensively as the other two examples. Alternatively, it might reflect a slightly deeper water during the Paleocene on Svalbard as compared to the other two localities (e.g. Kiel, 2010), or an effect of a general impoverishment of benthic faunas in the early Palaeogene (e.g. Roy, 1994). It is also likely that somehow lower diversity of the Fossildalen shallow water seep fauna as compared to other shallow water seep faunas is caused by unstable environment and frequent turbidity currents sweeping through the seep during its activity. Traces of such activity are carbonate-filled specimens of *C. conradi* found within siltstones outside the seep, and pockets of clastic material in authigenic carbonate crust found within these specimens. Turbidite currents can be an important factor shaping seep environments, dispersing epifauna and effectively removing it from the seep ecosystem (e.g. Sandy et al., 2012) and covering the seep surface with a blanket of clastic material (e.g. Agirrezabala et al., 2013), sealing of the carbonate and sulphidic substrate for seep-inhabiting biota. The latter factor could potentially contribute to the small size of Fossildalen seep lucinids, which are much smaller than the majority of seep lucinids found elsewhere (Kiel, 2013) and with respect of their size most similar to the shallow water lucinid assemblage from the Late Cretaceous (Cenomanian) Tropic Shale seep carbonates from Western Interior Seaway, USA (Kiel et al., 2012). Small size of Tropic Shale seep lucinids could potentially result from frequent gas explosions and toxic conditions, killing of the lucinids before they could fully grow (S. Kiel, 2016, personal communication).

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 we found in Fossildalen are borings in the wood fragments found in the seep carbonates (Fig. 8B). The most significant marine wood-borers are teredinid (Turner, 1966; Nair and Saraswathy, 1971) and xylophagain 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 in submerged wood (Wolff, 1979; Rice, 1985). Teredinids are especially widespread in the tropical shallow waters, most efficient in attack floating wood (Nair and Saraswathy, 1971). Their borings are elongated and aligned along the grain of the wood, with walls covered with calcareous linings (Turner, 1966). A single shell of wood-boring bivalve (Fig. 11C) and borings found in the wood are well within the size range of teredinids; however, the borings lack calcareous linings. This is not necessarily for the identifications 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. On the contrary to teredinids, xylophagains attack the wood on the seabed and are most common in the deep sea (Knudsen, 1961), although not exclusive to it (Santhakumaran, 1980). Great majority of xylophagains do not exceed 10 mm in diameter (Knudsen, 1961) and the borings observed in this study are nearly twice the diameter of usual xylophagain infestations. They also lack phecals characteristic for xylophagain borings, i.e. wood-rich phecals linings of the inner walls of the borings (Kiel et al., 2009). As in the case of calcareous linings, the latter is not determinant, and could simply be a preservation issue and a matter of loss of phecals due to taphonomy. Investigated borings almost certainly have not been made by chelurid and limnoriid crustaceans, as these are much smaller in

diameter (1–2 mm). Some Fossildalen wood borings could theoretically be 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 also be attracted to the site by food, shelter and substrate provided by the sunken wood (Wolff, 1979). However, the fauna does not contain any species typically associated with sunken driftwood of similar age (Kiel and Goedert, 2006; Kiel, 2008a; Kiel et al., 2009), and the overall influence of wood on the faunal community of Fossildalen seep carbonates is at the moment difficult to ascertain.

6.4. Macroevolutionary considerations

Fossildalen seep is heavily dominated by a large thyasirid bivalve *C. conradi*. Thyasirids are known at seeps from the Early Cretaceous (Berriasian) onwards (Hryniewicz et al., 2014), however in a great majority of fossil seep sites they are rather uncommon and accessory (Kiel, 2010). Some of the exceptions are the latest Cretaceous–earliest seeps, where large thyasirids occur in large numbers and often dominate the seep fauna. Sada Limestone (Campanian–Maastrichtian) from Shikoku, Japan (Nobuhara et al., 2008), contains mass accumulations of a large thyasirid ‘*Aphrodina*’ *hataii* (Katto and Hattori, 1965), exceeding 90 mm in length (K. Hryniewicz, own data). It co-occurs with somehow less numerous lucinid, solemyid, worm tubes and a species of a large gastropod *Elmira* (Cooke, 1919) of yet uncertain taxonomic affinity (Kiel and Peckmann, 2007). Another example of latest Cretaceous–earliest Palaeogene seeps with mass occurrences of thyasirid bivalves are the Maastrichtian seeps from James Ross Basin, Antarctica, with numerous specimens of ‘*Thyasiria*’ *townsendi* (very likely a species of *Conchocele*), occurring together with solemyid and lucinid bivalves, and yet unidentified gastropods (Little et al., 2015). The Paleocene

Fossildalen finding constitutes the third seep in a relatively short latest Cretaceous–earliest Palaeogene interval, when exceptionally large thyasirids occur at seeps more frequently as compared to other time intervals. This is even more striking considering that only two more seep faunas from this time interval other than the above mentioned thyasirid-bearing faunas are known. These are some Maastrichtian seep faunas from Western Interior Seaway, USA (Metz, 2010); and Paleocene Panoche Hills seeps from California, USA (Schwartz et al., 2003). This common occurrence of large thyasirids at seeps during the latest Cretaceous and Paleocene is puzzling. It could perhaps be explained by a lower global sea level (Haq et al., 1987; Van Sickel et al., 2004) and global cooling at that time (Linnert et al., 2014). Shallower latest Cretaceous–earliest Palaeogene seas could be more favourable to Conchocele, which seems to prefer shelf to middle bathyal water depths (Kamenev et al., 2001; Okutani, 2002). The other cause might be that thyasirids, among them 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 Paleocene oceans could promote more efficient dispersal of thyasirids.

Molluscan fossils typically associated with the majority of Mesozoic and Cenozoic hydrocarbon seep carbonates have not been recorded in the current study, such as paskentanid, provannid and hokkaidoconchid gastropods (e.g. Kiel, 2008b, Kiel et al., 2008; Kaim et al., 2014), large kalenterid bivalve *Caspiconcha* (Kelly et al., 2000; Jenkins et al., 2013) and bathymodiolin mussels and vesicomid clams (Squires and Gring, 1996; Amano and Kiel, 2007; Kiel and Amano, 2013). The absence of paskentanid gastropods could simply be an age issue, as they range from Late Jurassic (Oxfordian) to Late Cretaceous (Turonian; Kaim et al., 2014), disappearing from seeps long before the onset of seepage in Fossildalen. The same applies to *Caspiconcha*, which is most common at latest Jurassic (Tithonian) to Early

Cretaceous seeps, with last known seep occurrence known from the Late Cretaceous (Campanian; Jenkins et al., 2013). Hokkaidoconchid gastropods range from the Late Jurassic (Oxfordian) to the Eocene (Kiel and Hansen, 2015), therefore could potentially occur in Fossildalen seep carbonates. The same applies to provannid gastropods, which are known from the Late Cretaceous (Cenomanian) onwards (Kaim et al., 2008). Absence of both groups from Fossildalen seep carbonates could therefore be a function of more local, ecological factors. Both vesicomysids and bathymodiolins appear at seeps in the mid-Eocene (Amano and Kiel, 2007; Kiel and Amano, 2013), therefore their absence at Fossildalen could also be related to age. The appearance of both vesicomysid and bathymodiolin bivalves in the Eocene — sometimes associated with the onset of ‘modern’ seep faunas — was explained by a rapid extinction-repopulation of deep-marine chemosynthesis-based settings caused by oceanic anoxic event around the Paleocene–Eocene transition (Vrijenhoek, 2013), or by an increase of seawater sulphate concentrations in the Eocene (Kiel, 2015). The absence of bathymodiolins and vesicomysids from Paleocene Fossildalen seep corroborates the observation that the radiation of bathymodiolins and vesicomysids took place in the Eocene. Caution should be made, however, as the shallow water setting of Fossildalen seep is not favourable for bathymodiolins and vesicomysids, and could have influenced their distribution.

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

Paleocene age of the deposit precedes a biotic crisis associated with oceanic anoxic event around the Paleocene–Eocene transition. The moderately diverse fauna associated with the Fossildalen carbonates consists of molluscs with subordinate crustaceans, polychaetes and brachiopods. The most common mollusc in the fauna is a species of a large thyasirid bivalve *Conchocele*, which was much more broadly distributed during the latest Cretaceous–Paleocene than it is now. Apart from the species of *Conchocele*, the fauna does not contain any species which is typically associated with seeps of that age. Together with the moderately high diversity of the fauna, we interpret this faunal composition as typical of relatively shallow water setting of Fossildalen seep. No bathymodiolin and vesicomid molluscs have been found in the fauna, which corroborates the observation that both bivalve groups radiated into seep environments during the Eocene.

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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).

Fig. 2. The assumed locality of Hägg (1927), 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 Palaeogene succession of Central Cenozoic Basin after Spielhagen and Tripathi (2009), the star marks approximate position of the sampled locality. Depositional environments of particular formations after Helland-Hansen (2010).

Fig. 3. Dinoflagellate cyst and foraminifera recorded in this study. A) *Oligosphaeridium* complex, ZPAL V.50/1; B) *Spiniferites ramosus*, ZPAL V.50/8; C) *Paleoperidinium 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.

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 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.

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 withing 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.

Fig. 7. Silification of Fossildalen 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 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.

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

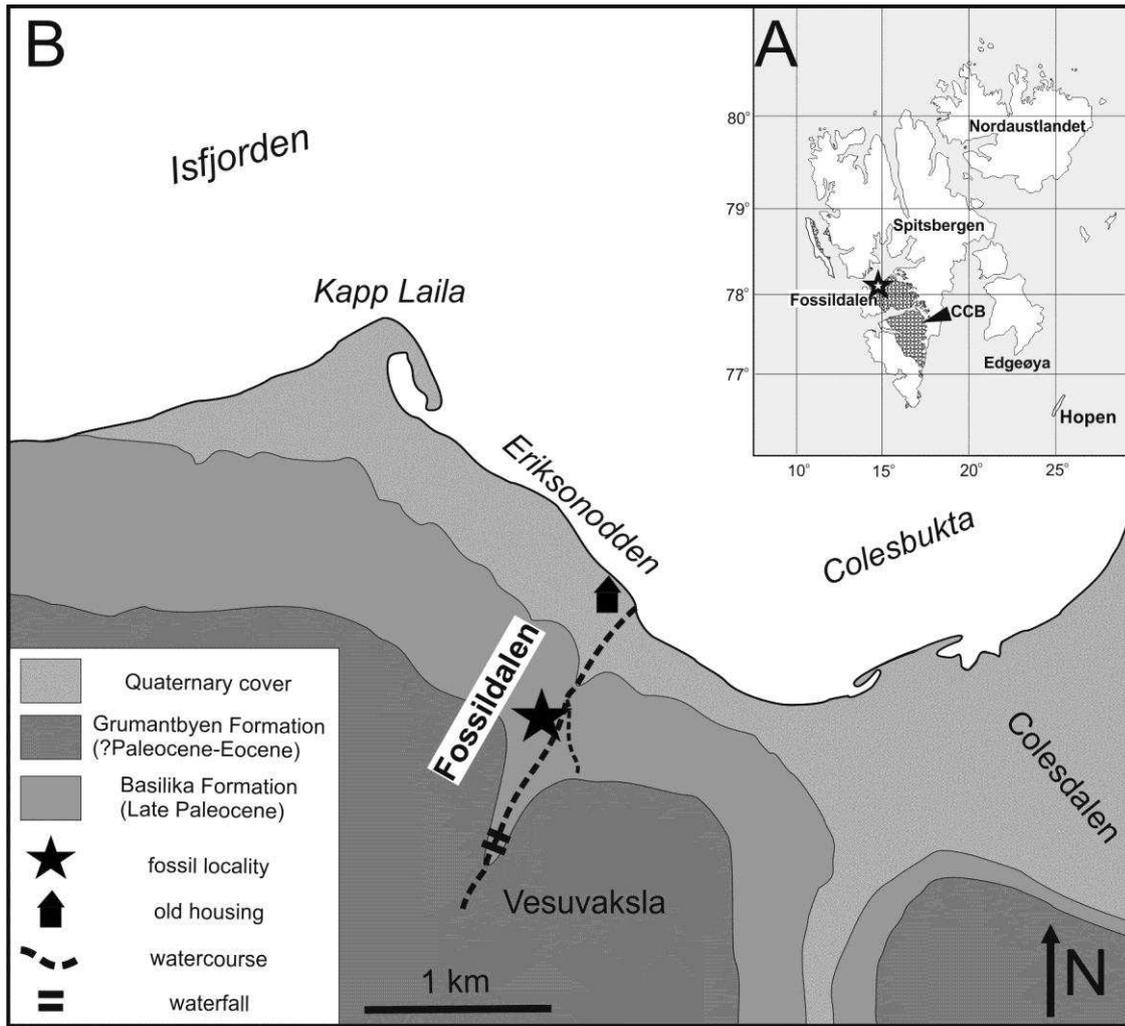
Fig. 10. Total ion chromatogram of the hydrocarbon fraction obtained from Fossildalen seep carbonates. Closed circle indicates n-alkanes, and numbers above them indicate carbon numbers. PMI, pentamethylcosane. The compound-specific stable carbon isotopic composition of PMI is shown in parentheses as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

Fig. 11. Petrography of bivalve-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.

Fig. 12. Fossils from the Paleocene hydrocarbon seep carbonates Fossildalen, Spitsbergen, Svalbard. A) *Conchocele conradi* 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* sp., NRM-PZ Mo149147; D) *Protobranchia* sp., GPIBo 152; E) *Mytilidae* 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.

Table 1. Stable isotope compositions of Paleocene Fossildalen seep carbonates.

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



PALAEOGENE		SYSTEM	
PALAEOCENE		SERIES	
UPPER			
THANETIAN		STAGE	
D2	D3	D4	D5a
			<i>Cerodinium dartmoorium</i>
			<i>Cerodinium striatum</i>
			<i>Palaeoperidinium pyrophorum</i>
			<i>Oligosphaeridium complex</i>
			<i>Spiniferites ramosus</i>

