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Hydrocarbon seeps from close to the Jurassic–Cretaceous boundary, Svalbard

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ABSTRACT

Fifteen carbonate bodies, interpreted as having been formed at hydrocarbon seeps, have been found in the Sassenfjorden area of Spitsbergen, Svalbard. The bodies, up to 5 m wide, are found in the siltstones and mudstones of the uppermost Slottsmøya Member, in the Upper Jurassic to lowermost Cretaceous Agardhfjellet Formation. The age of the seeps is close to the Volgian–Ryazanian (Jurassic–Cretaceous) boundary, and the Mjølnir impact event in the Barents Sea. The Sassenfjorden area carbonates show complex and heterogeneous structures typical of hydrocarbon seeps, including zoned (botryoidal) cement textures, fissure-infilling sparite, and breccias. Stable isotope analyses show highly negative δ^{13}C values (down to ca. −43‰ VPDB) in the zoned carbonate cements, consistent with authigenic precipitation in a hydrocarbon-rich environment. Oxygen isotopes indicate secondary hydrothermal activity. The species-rich, well-preserved fauna includes at least 13 species of small to medium sized bivalves, some of which are abundant, as well as rarer rhynchonelliform and lingulid brachiopods, gastropods, echinoderms, sponges, and serpulid and probable vestimentiferan worm tubes. Although several bivalves (solemyids, lucinids, and probably *Thyasira* and *Nucinella*) had chemosymbionts, the Sassenfjorden seep fauna contains few, if any, seep obligate taxa, consistent with formation in a relatively shallow-water paleoenvironment. The seeps contain the earliest record of thyasirid bivalves, and a species-rich (six) brachiopod fauna including the first lingulid recorded in a seep environment. Ammonites, belemnites and large wood fragments represent *ex situ* fossils in the seep carbonate bodies.

1. Introduction

Hydrocarbon seeps and associated structures, such as pockmarks and authigenic carbonates, have in the last decades emerged as important and common elements of modern continental shelf environments (e.g. Judd and Hovland (2007)). The dominant seeping hydrocarbon is usually methane, and the seeps can provide clues to the positions of deep or shallow gas reservoirs and fluid migration paths. Ecologically, hydrocarbon seeps can provide a locally important nutrient source mediated by chemoautotrophic micro-organisms, often in symbiosis with macrobiota such as bivalves (e.g. solemyid, vesicomyid, lucinid and thyasirid clams, and bathymodiolin mussels) and vestimentiferan worms (e.g. Sibuet and Olu (1998); Levin (2005)). Perhaps even more crucially, the methane-derived carbonate constitutes a hard substrate that allows colonization by sessile organisms (such as serpulid worms, sponges and crinoids) that can not otherwise settle on the predominantly muddy sea floor. Together with the altered current conditions and microhabitats caused by the associated pockmark depressions, the hydrocarbon nutrient input and the hard substrate may make hydrocarbon seeps one of the most important contributors to ecological heterogeneity and biodiversity in many shelf environments (Webb et al., 2009). There is evidence for a bathymetric control on the ecological and taxonomic structure of modern hydrocarbon seep communities. The number of taxa restricted to that environment (i.e. obligate taxa) decreases from the slope and deep shelf onto the shallow shelves, such that all obligate chemosymbiotic taxa disappear above around 200 m. In contrast, the number of predators and background taxa increases from slope to shallow shelf (e.g. Carney (1994); Levin et al. (2000); Sahling et al. (2003)).

Considering their present importance, there has been great interest in the search for hydrocarbon seeps in the geological record, both as indicators of past biogeochemical processes (e.g. Peckmann and Thiel (2004)) and to reconstruct the evolutionary lineages of seep-related organisms (e.g. Kiel and Little (2006)). Campbell (2006) reviewed the record of ancient hydrocarbon seeps and their associated fossil communities. Cenozoic seeps are numerous, with a near global

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distribution, but prior to that the record becomes increasingly sparse and localized (Campbell, 2006), such that there are only six known Jurassic localities. These are the Sinemurian Kilve seeps from Southern England (Allison et al., 2008) and the Toarcian Los Molles seep from the Neuquén Basin, Central Argentina (Gómez-Pérez, 2003), neither of which are typical seep carbonate bodies and will not be considered further, the Oxfordian seeps of Beauvoisin, France (Gaillard et al., 1992; Peckmann et al., 1999; Senowbari-Daryan et al., 2007; Kiel, 2010), and the Tithonian seeps from Alexander Island, Antarctica (Kelly et al., 1995; Kaim and Kelly, 2009) and the Great Valley Group, California (Paskenta and NW Berryessa; e.g. Campbell et al. (1993); Campbell (2006); Kiel et al. (2008b); Kiel (2010)).

In this paper we give a preliminary report on fifteen small carbonate bodies, which we interpret as ancient hydrocarbon seeps, from near the Jurassic–Cretaceous boundary in central Spitsbergen, Svalbard. This interpretation is supported by petrographic and stable isotope data. The seeps constitute the seventh Jurassic example and contain an assemblage of benthic fossils that is ecologically and taxonomically different from most Mesozoic seep fossil assemblages, having, for example, few obligate seep species and many background taxa, including a diversity of brachiopods.

2. Geological setting

The fifteen studied seep carbonate bodies occur along ca. 10 km of strike in the Slottsmøya Member of the Agardhfjellet Formation (Dypvik et al., 1991a) in the Sassenfjorden area of central Spitsbergen (Fig. 1). All the bodies are found at a similar stratigraphic level 5–11 m below the top of the Slottsmøya Member (Fig. 2), except one which was found as a loose block downsection and may have been recently slumped into that position. The largest seep carbonate body (locality 9; Figs. 1 and 3) is ca. 5 m in diameter, but has been fractured by frost wedging, and thus some of the lateral extent may be due to downslope-transported loose blocks. The other seep carbonate bodies are smaller, being less than 2 m in diameter, and many also have downslope fields of scattered small carbonate blocks.

The Slottsmøya Member comprises dark gray to black silty mudstones, often weathering to paper shales, with occasional discontinuous silty, sideritic beds and sideritic and dolomitic concretions. The mudstones contain a benthic macrofossil fauna of scaphopods, serpulids and bivalves, including *Buchia*, *Goniomya* and pectinids (Birkenmajer et al., 1982). These fossils are also found in the sideritic beds and concretions, together with protobranch bivalves and echinoderms, comprising articulated and partially articulated asteroids, ophiuroids, crinoids and regular echinoids, the preservation of which suggests very low energy conditions during deposition and/or rapid sedimentation. The nektic fauna in the Slottsmøya Member includes ammonites, exceptionally large (4 cm) coleoid arm hooks, and well-preserved marine reptiles. Unusually for a Jurassic sedimentary marine unit, belemnites are rare in the Slottsmøya Member.

The Agardhfjellet Formation was deposited in an open marine shelf setting, under generally low oxygen conditions (Nagy et al., 1988). In parts, the formation is rich in organic carbon, up to 12%, but decreasing to 1.5–2% in the uppermost part (Dypvik, 1985; Nagy et al., 1988). In the paleogeographic reconstructions given by Dypvik et al. (2002), paleoshorelines were situated a few hundred kilometers to the west and north. The sedimentology, geochemistry and paleontology of the Agardhfjellet Formation have been subjected to intensive research (e.g. Dypvik (1985); Nagy et al. (1988); Dypvik et al. (1991b); Nagy and Basov (1998); Krajewski (2004)), but the seep carbonate bodies described here were previously unreported.

The position of the Sassenfjorden seep carbonate bodies near the top of the Slottsmøya Member places them close to the Volgian–Ryazanian boundary (Nagy and Basov, 1998). Some carbonates contain numerous craspeditid ammonite specimens belonging to the Upper Volgian genera *Craspedites* and *Taimyroceras*, whereas other carbonates contain Upper Ryazanian taxa like *Surites and Bojarkia.* Acid dissolution residues of the carbonate bodies contain specimens of the agglutinated foraminifera *Recurvoides obskiensis*, *Evolutinella schleiferi* and *Ammobaculites* cf. *gerkei*, which belong to the upper F7 and lower F8 foraminiferal zones of Nagy and Basov (1998), spanning the uppermost Volgian to Ryazanian age range. Correlation between the Jurassic–Cretaceous stratigraphic units of the Tethyan and Boreal regions remains problematic. The Volgian Slottsmøya

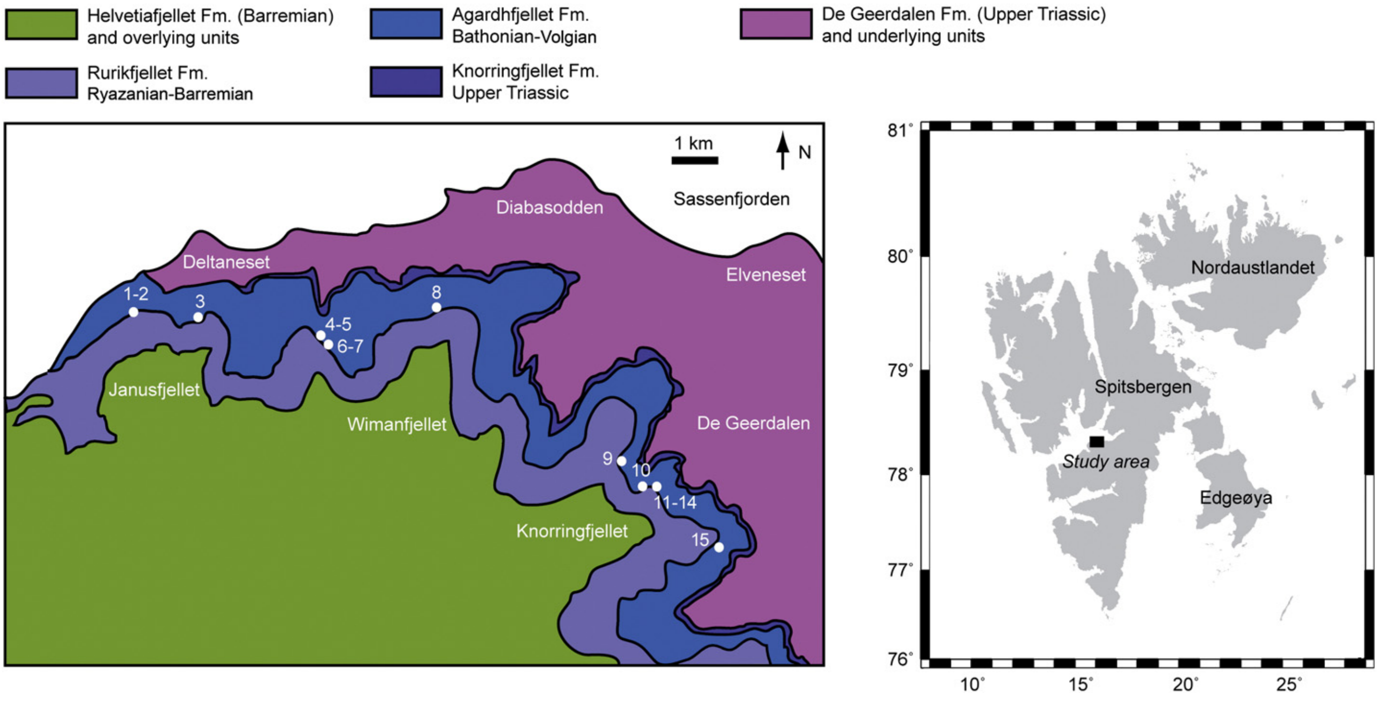

Fig. 1. Highly simplified geological map of the Sassenfjorden area in central Spitsbergen, with seep carbonate bodies at localities 1–15 indicated.

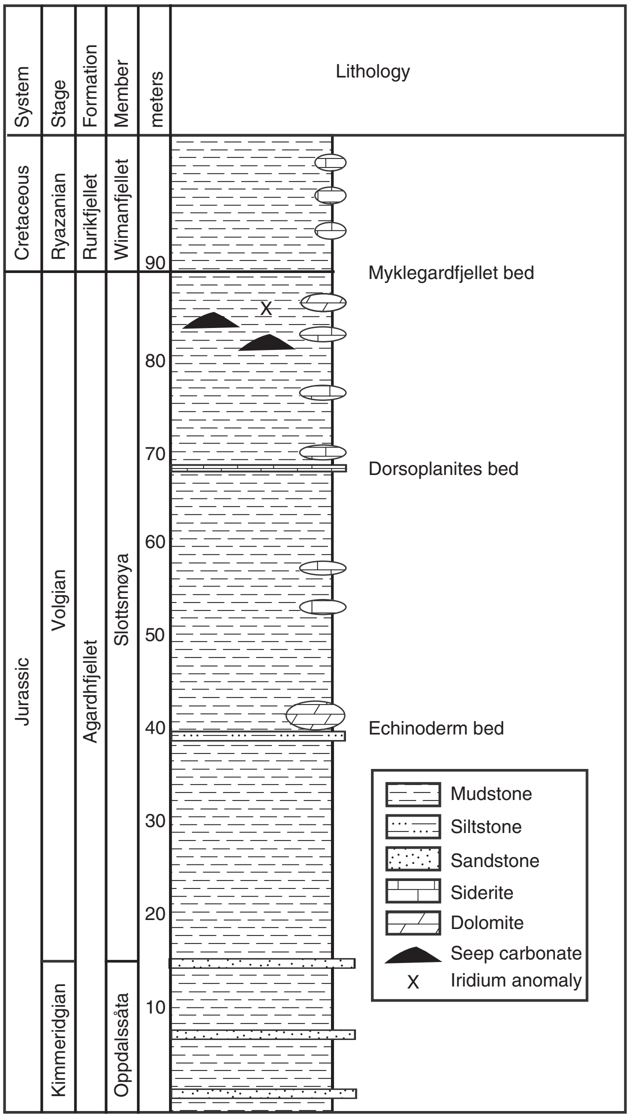

Fig. 2. Simplified stratigraphy of the Slottsmøya Member in the Sassenfjorden area.

Member has traditionally been regarded as Tithonian. However, in the most recent geologic timescale of Ogg (2004), the Upper Volgian was moved to the Lower Cretaceous. According to this interpretation, the oldest carbonate bodies could be as young as Lower Berriasian. However, Zakharov and Rogov (2008) argue for moving the Upper Volgian back to the Upper Jurassic. In light of this continuing controversy and until further evidence appears, we have here chosen in accordance with the traditional chronostratigraphy to assign the seep carbonate bodies to near the Jurassic–Cretaceous boundary.

Climatic conditions in the uppermost Jurassic in the High Boreal region are not yet fully constrained. Stable isotope data from belemnites in Svalbard have given seawater paleotemperatures of 7.6 °C in the Callovian and 8.1 °C in the Valanginian (Ditchfield, 1997). For the more remote location of Western Siberia, Price and Mutterlose (2004) recognized a trend towards lower temperatures starting in the late Volgian, culminating in the late Valanginian (2–14 °C), but with a relatively warm phase (11–21 °C) in the late Volgian to earliest Ryazanian. A simple calculation from only two biocalcite samples from the seeps described here, assuming a seawater composition of −1‰ SMOW, gives temperatures of 16.1 °C (belemnite; $\delta^{18}O = -0.82$‰ VPDB) and 13.6 °C (brachiopod; $\delta^{18}O = -0.24$‰ VPDB), i.e. in general accordance with the results from Western Siberia.

3. Methods

The Sassenfjorden seep carbonate bodies were sampled for paleontological and petrographical study over four field seasons (2007–2010) in the area. The smaller carbonates at localities 1–8 and 10–15 were bulk sampled from exposed blocks and scattered downslope debris. The more in-situ nature of the large seep at locality 9 allowed more controlled sampling. Sampling effort of the seep carbonate bodies was not even, with some being sampled only once, while others, particularly at localities 9 and 3, were sampled on multiple occasions.

Selected carbonate samples from locality 9 were analyzed for stable isotopes ($\delta^{13}C$ and $\delta^{18}O$) at the Institute for Geosciences, University of Bergen. Powdered samples were analyzed on Finnigan MAT 251 and MAT 253 mass spectrometers coupled to automated Kiel devices. The data are reported on the VPDB scale calibrated with NBS-19. The long term analytical precision of both systems as defined by the external reproducibility of carbonate standards (>8 mg) over

Fig. 3. Field image of the largest seep carbonate in the Sassenfjorden area (locality 9), showing the fragmented state of preservation.

periods of weeks to months exceeds 0.05‰ and 0.1‰ for $\delta^{13}C$ and $\delta^{18}O$ respectively.

Petrographic thin sections were examined by plane-polarized and reflected light microscopy. Cathodoluminescence imaging used a Nuclide ELM-2A Luminoscope mounted on a Nikon Labophot-2 camera, at 13.5 kV and 1 mA.

Samples from locality 9 were treated with 10% formic acid, sieved, dried and picked for agglutinated foraminiferans, lingulids, dolomitized peloids and other insoluble remains.

4. Results

4.1. Petrography and stable isotope analyses

The carbonate fabrics in the Sassenfjorden seep carbonate bodies are highly complex and heterogeneous, but nevertheless a consistent paragenetic sequence can be identified in them all. The earliest phase is characterized by black to gray micrite (phase m), often massive (Fig. 4A), or interfingering with a mottled wackestone (phase w; Fig. 4B)

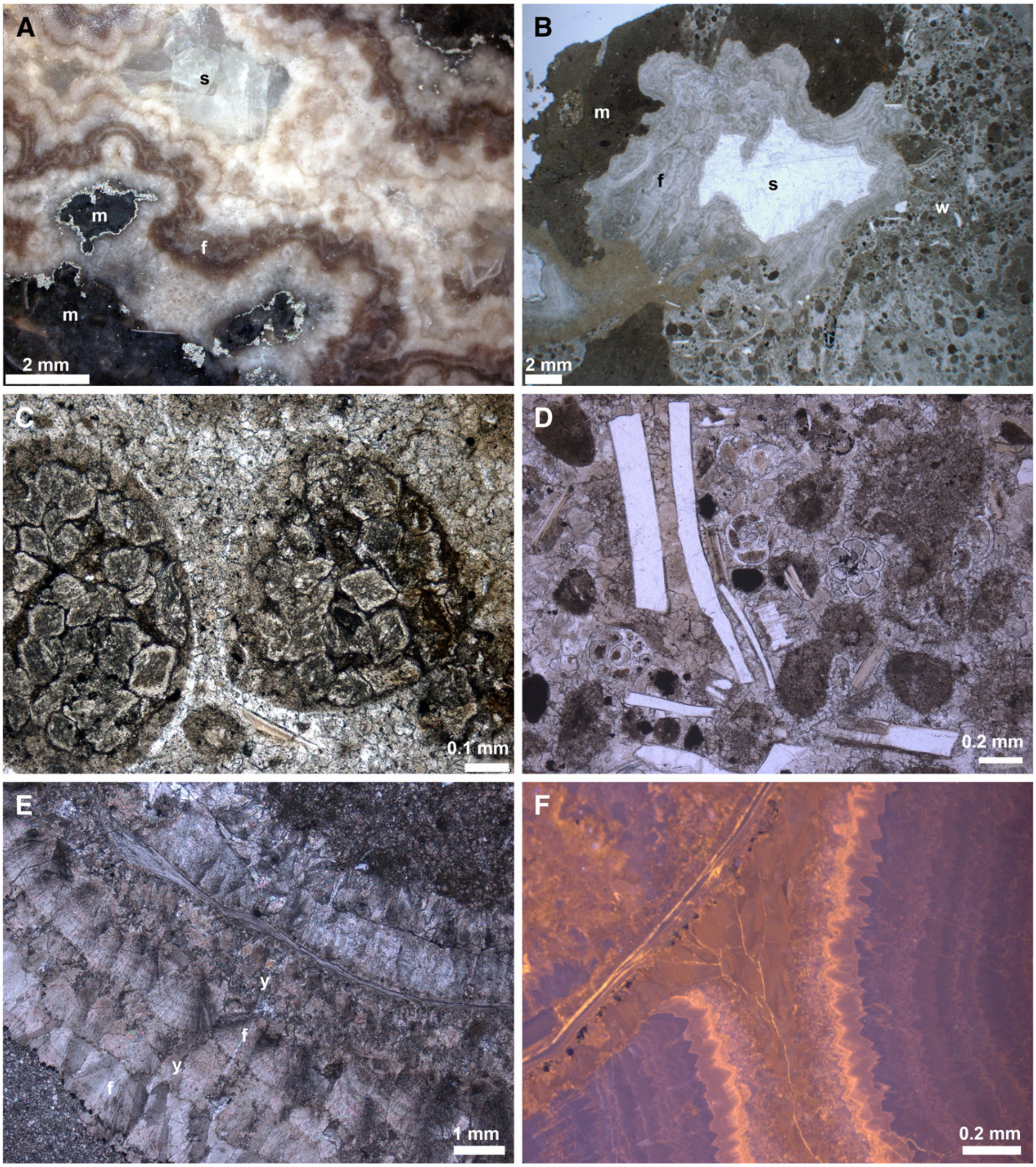

Fig. 4. Petrography of the seep carbonates in the Sassenfjorden area. A: Several phases seen in polished hand specimen, reflected light. m: Early micrite with pyrite lining. f: Fibrous, botryoidal calcite. s: Late blocky sparite. PMO 170.970. B: Several phases seen in thin section, transmitted light. w: Wackestone. PMO 170.965. C: Peloids in wackestone, with dolomite. PMO 170.958. D: Coquina of macrofossil fragments and foraminiferal tests in a matrix of yellow-brown calcite. PMO 170.975. E: Close-up of brachiopod shell enclosed by late-phase carbonate cement. The shell is encrusted by alternating layers of yellow anhedral calcite (y) and fibrous calcite (f). PMO 214.779 F: Fibrous, laminated calcite with rhombic terminations, viewed in cathode luminescence. PMO 170.962.

rich in peloids (Fig. 4B, C) and micro- and macrofossils (4D), grading into shell hash composed of reworked skeletal material (Fig. 5F). The carbonate matrix inside peloids is in some cases replaced with euhedral zoned dolomite (Fig. 4C), which has been found only inside these peloids. They are not directly comparable with the clearly structured microcoprolites described from the Jurassic hydrocarbon seeps of France (Senowbari-Daryan et al., 2007), broadly ascribed to crustaceans.

The micrite often gives a corroded impression, and sometimes has a lining of pyrite (Fig. 4A). A brown to yellow calcite (phase y) is often found encrusting micrite and macrofossils (Figs. 4D, E, 5C, F). This phase is followed by a fibrous calcite (phase f), sometimes with rhombic termination (Fig. 4F), and with fanlike morphology and rolling extinction under cross polarization (Figs. 4E, 5B). The fibrous calcite can also grow directly on micrite or on fossils, and often alternates with yellow calcite in concentric bands (Fig. 4E), producing well-defined botryoids with radii of up to a centimeter or more (Fig. 5B). This phase displays fine lamination (Fig. 5B), which is sometimes stromatolite-like (Fig. 5A). A later phase of rather coarse-grained but otherwise homogenous silt-grade carbonate is sometimes found as a geopetal infilling in worm tubes and bivalves (Fig. 5D). Like the wackestone, this phase can contain dark, ovoid peloids. Coarse, blocky calcite spar represents the last phase(s) in the sequence, filling primary voids (Figs. 4A, B, 5D) and found in fractures that cut through

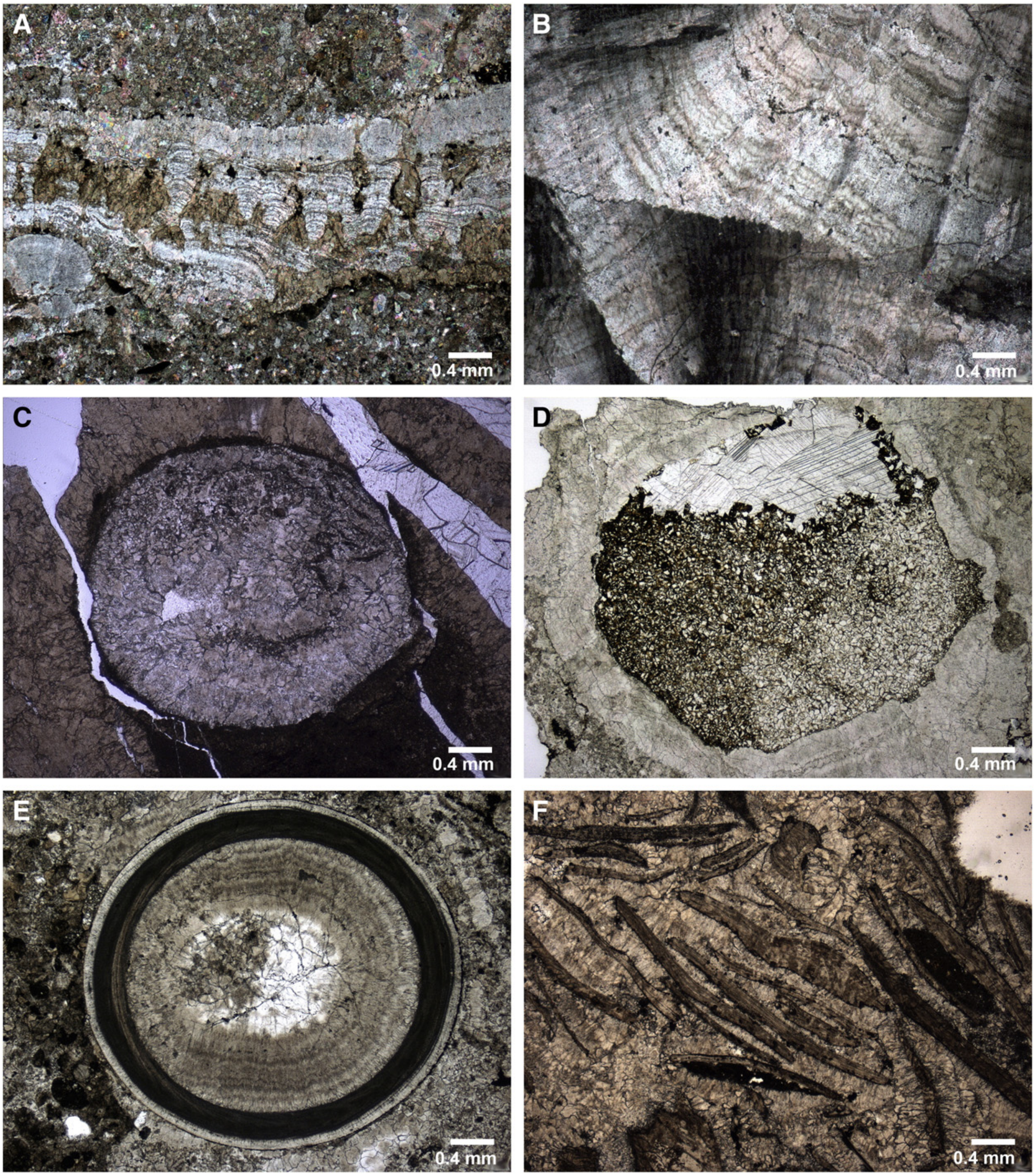

Fig. 5. Petrography of the Sassenfjorden seep carbonates, continued. A: Laminated, fibrous calcite with stromatolitic structure. PMO 171.022B. B: Laminated, fibrous calcite. The stylolitic suture indicates late diagenetic pressure dissolution. PMO 170.963. C: Possible vestimentiferan worm tube encrusted by yellow calcite. Late diagenetic fractures are filled with blocky sparite. PMO 170.972. D: Worm tube encrusted by yellow calcite, and with geopetal infilling of carbonate silt. The void has been filled with late diagenetic sparry calcite. PMO 171.029A. E: Serpulid worm tube, PMO 171.023B. F: Hash of imbricated shelly fragments in yellow calcite, PMO 214.700.

all previous phases (Fig. 5C). Hollow vugs are present in the carbonate bodies, particularly in the interior spaces of articulated bivalves and brachiopods.

When freshly broken the carbonates have a distinct smell of petroleum and black colored patches on some polished surfaces may be bituminous.

Table 1 and Fig. 6 show the distribution of $\delta^{13}C$ and $\delta^{18}O$ isotope values of various carbonate cement phases and shells from the large seep carbonate body at locality 9. The different phases are well separated in the diagram. The dark micrites have moderately depleted $\delta^{13}C$ values (−15 to −23‰ VPDB) and $\delta^{18}O$ values between 0 and −5‰ VPDB. The late calcite spar(s) has similar $\delta^{13}C$ values, but $\delta^{18}O$ values that are strongly depleted (−17 to −19‰). There is a much greater scatter of $\delta^{13}C$ and $\delta^{18}O$ values within the fibrous calcite and wackestone phases, but these consistently have more depleted $\delta^{13}C$ values (down to −43‰) than the micrite and calcite spar. They are not as depleted in $\delta^{18}O$ as the calcite spar. A brachiopod shell and a belemnite from the same carbonate have rather different isotope signatures to the cement phases, and are close to normal marine.

4.2. Fossil content

Table 2 shows the macrofossil content of the Sassenfjorden seep carbonate bodies. The macrofossils include benthic elements (sponges, bivalves, gastropods, scaphopods, brachiopods, echinoderms, and tube worms) and allochthonous elements from surface waters (ammonites, belemnites and pieces of wood up to 40 × 150 mm in size). Microfossils include uncompacted agglutinated foraminiferans (see Section 2) and, visible in thin sections, calcareous foraminiferans, radiolarians, sponge spicules and ostracods. The benthic macrofossils are not evenly distributed within or between individual seep carbonates (Table 2). Most of the smaller bodies have relatively few, scattered specimens, and diversity is often low, but other carbonates (localities 3 and 9) are very fossil-rich and diverse (up to 18 taxa), with specimens of different species co-occurring or in monospecific clusters. Bivalves and brachiopods are very often articulated (Fig. 7), but layers of shell hash also occur in some of the carbonates. Shell preservation of the benthic macrofossils varies, with the original shell structure of the brachiopods and calcitic shelled bivalves being retained, but the shells of aragonitic bivalves and gastropods are often recrystallized to sparry calcite. The majority of the benthic taxa belong to mobile groups living on or in soft sediment, but the colonization of hard carbonate substrates is indicated by the occurrence of rhynchonelliform brachiopods and cementing taxa (oysters and serpulid worms), although these taxa could have attached onto pre-existing shells.

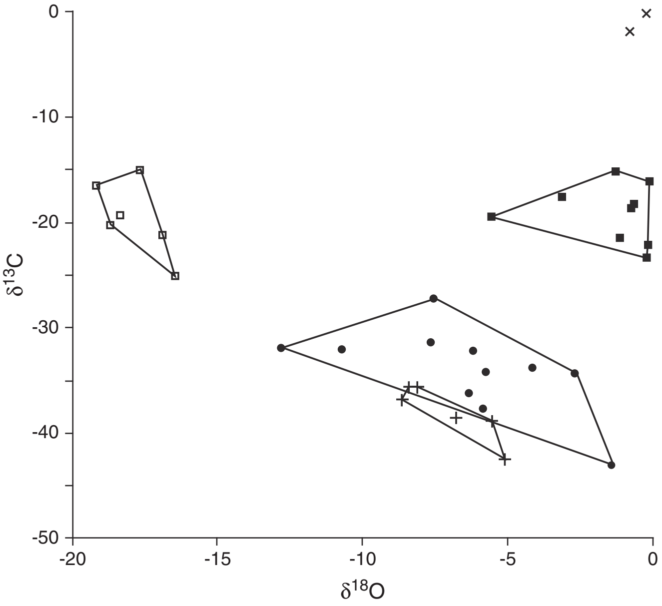

Fig. 6. Carbonate stable isotopes in the Sassenfjorden carbonate seep body, locality 9. Filled squares: dark micrite. Open squares: sparite. Plus signs: Zoned calcite. Crosses: Macrofossil calcite (brachiopod above, belemnite below). Dots: Wackestone.

Table 1
Stable isotopes from carbonates in a Sassenfjorden seep, locality 9.

Sample	$\delta^{18}O/^{16}O$	$\delta^{13}C/^{12}C$	Mineral phase
F1	−8.11	−35.60	Botryoidal
F2	−8.43	−35.61	Botryoidal
F3	−5.57	−38.83	Botryoidal
F4	−6.79	−38.61	Botryoidal
4-3	−5.09	−42.52	Botryoidal
4-4	−8.64	−36.89	Botryoidal
F5	−18.65	−20.26	Sparite
F6	−18.33	−19.41	Sparite
F7	−16.44	−25.07	Sparite
5-1	−17.66	−15.05	Sparite
4-2	−19.16	−16.51	Sparite
9-1	−16.86	−21.2	Sparite
6-1	−0.61	−18.28	Dark micrite
7-1	−1.09	−21.49	Dark micrite
9-2	−1.23	−15.15	Dark micrite
13-1	−5.5	−19.53	Dark micrite
15-2	−3.11	−17.65	Dark micrite
12-2	−0.13	−22.12	Dark micrite
10-2	−0.18	−23.33	Dark micrite
15-1	−0.05	−16.21	Dark micrite
12-3	−0.72	−18.69	Dark micrite
BRK1	−0.24	−0.29	Biocalcite (brachiopod)
BE1	−0.82	−1.99	Biocalcite (belemnite)
1-1	−7.66	−31.53	Wackestone (shell hash)
8-1	−6.16	−32.27	Wackestone (shell hash)
9-3	−7.56	−27.41	Wackestone (shell hash)
10-1	−4.12	−33.93	Wackestone (shell hash)
11-1	−10.72	−32.2	Wackestone (shell hash)
4-1	−12.79	−32	Wackestone
12-1	−6.31	−36.27	Wackestone
13-2	−5.83	−37.8	Wackestone
14-1	−5.74	−34.29	Wackestone
14-2	−2.69	−34.39	Wackestone
3-1	−1.41	−43.22	Wackestone

The benthic macrofauna in the Sassenfjorden seep carbonate bodies is dominated by small to medium sized bivalves. Gastropods, brachiopods and worm tubes are less common; echinoderms (crinoids and regular echinoids), sponges and scaphopods are rare. Species richness within all these groups is likely to be higher than shown in Table 2 because the state of preservation precludes easy identification of many specimens (particularly the gastropods and the small, articulated bivalves). Further detailed taxonomic work is on-going. The bivalves belong to at least 13 species (Fig. 7A–K, M–O, Q) with a variety of modes of life, including infaunal and epifaunal taxa (Table 2). In the context of hydrocarbon seeps the presence of bivalves that probably depended on symbiotic bacteria for their nutrition is significant, i.e. solemyids (Fig. 7H), lucinids (Fig. 7D–E), *Thyasira* (Fig. 7A–C) and possibly *Nucinella* (Fig. 7F–G). *Buchia* (Fig. 7I) is by far the most common bivalve, and is present in all but three of the seep carbonates, as well as abundantly in the surrounding Slottsmøya Member mudstones. Gastropods include unidentified small high-spired taxa (Fig. 7P), as well as a large species (up to 70 mm tall) of the vetigastropod *Eucyclus* (Fig. 7L).

Brachiopods are taxonomically diverse for seeps, but not abundant as individual specimens. Several genera have been provisionally identified (Table 2). Terebratulids (Fig. 7S–T) are represented by elongate morphoforms that are referred to '*Praelongithyris*' and rounded forms referred to '*Cyrtothyris*' (Fig. 7S). These taxa were also provisionally identified by Owen (1976) from the Early Cretaceous of Greenland. One specimen of a long-looped terebratellid has been found, referred to '*Zittelina*' (Fig. 7T). Rhynchonellids are

Table 2
Preliminary checklist of macrofaunal taxa from Sassenfjorden seep carbonates. Mode of life codes for benthic taxa: ES = epifaunal suspension feeder, CES = cemented epifaunal suspension feeder, SIS = shallow infaunal suspension feeder, ID = infaunal deposit feeder, IBS = infaunal with bacterial symbionts, DIS = deep infaunal suspension feeder, EHD = epifaunal herbivore and/or detritivore, MC = microcarnivore, C = carnivore, SBS = semi-infaunal with bacterial symbionts. No fossils were recovered from locality 6.

Taxa/seeps	1	2	3	4	5	7	8	9	10	11	12	13	14	15	Mode of life
Sponges			+		+										ES
Brachiopods															ES
Lingula sp.	+				+						+			+	SIS
‘*Praelongithyris*’ sp.			+				+	+		+	+				ES
‘*Cyrtothyris*’ sp.						+		+		+					ES
‘*Lacunosella*’ sp.			+			+		+	+	+	+				ES
‘*Monticlarella*’ sp.								+							ES
‘*Zittelina*’ sp.								+							ES
Bivalves															
Malletiid sp. 1		+	+				+	+							ID
Malletiid sp. 2							+				+				SIS
Solemyid			+		+		+	+			+			+	IBS
Nucinella sp.		+	+	+	+			+			+			+	?IBS
Oxytoma sp.		+	+		+			+			+			+	ES
Pectinids	+		+	+			+	+							ES
Buchia spp.		+	+	+	+	+	+	+	+		+			+	ES
Pseudolimea sp.			+	+				+							ES
Ostreoidean			+												CES
Lucinids								+							IBS
Thyasira sp.								+							?IBS
Arcticid			+				+	+			+				SIS
Goniomya sp.			+												DIS
Indeterminate bivalves													+		
Gastropods															
Eucyclus sp.			+		+					+					EHD
High-spired sp.		+	+				+	+						+	EHD
Scaphopods								+							MC
Ammonites		+	+	+	+	+	+	+	+		+	+			
Belemnites				+				+							
Crustacean fragments				+											?C
‘Vestimentiferan’ tubes			+	+	+		+				+				SBS
Serpulid tubes			+				+								ES
Echinoid test plates and spines			+				+								EHD
Crinoid ossicles							+						+	+	ES
Wood fragments			+			+	+							+	
Benthic species richness	2	5	18	6	8	3	11	17	3	4	10	0	2	7	

represented by specimens provisionally assigned to the genera ‘*Lacunosella*’ (Fig. 7R) and ‘*Monticlarella*’. In addition, small specimens of *Lingula* (Fig. 7U) typically only a few mm in length (Fig. 7U) can be quite numerous in places in certain seep deposits (Table 2). Lingulids are previously described from the underlying Brentskardhaugen Beds of Middle Jurassic (Bathonian) age (Bäckstrøm and Nagy, 1985; Biernat and Emig, 1993).

Worm tubes belong to the serpulids (Fig. 5E) and possibly vestimentiferans (Fig. 5C). The latter have external ornament of longitudinal striations and thin, laminated tube walls, features known from modern carbonate replaced seep vestimentiferan tubes (Haas et al., 2009) and other presumed fossil counterparts (e.g. Peckmann et al. (2005)), although similar morphological features have been described in chaetopterid annelid worm tubes (Kiel and Dando, 2009). Only one crustacean macrofossil has been identified in the seep carbonates (Table 2).

5. Interpretations and discussion

5.1. Petrography and paragenetic sequence

The Sassenfjorden carbonate bodies contain many of the features now considered to be typical of hydrocarbon seep deposits (e.g. Beauchamp and Savard (1992); Campbell et al. (2002); Peckmann and Thiel (2004); Campbell (2006); Kiel and Peckmann (2008)). Campbell et al. (2002) and Campbell (2006) compiled stable isotope data from a variety of seep carbonates throughout the Phanerozoic, and identified several distinct groups. The carbonate isotopic composition from the Sassenfjorden seeps falls into their Group 1, typical of Paleozoic and Mesozoic seep sites. Moreover, different carbonate phases can be interpreted as representing degrees of diagenetic alteration, where the botryoids with phases y and f represent early diagenetic stages and the sparites (phase s) being precipitated at greater burial depth. Given the strong parallels with the carbonate phases and their relationships observed in seeps of similar age, it is possible to put the Sassenfjorden seeps into a similar conceptual framework. In this framework, the early micrite (phase m) represents diffuse seepage and the formation of authigenic carbonate close to the sea floor, preserving smaller fossils and fossil fragments. The resulting hardgrounds were covered by bacterial mats, under which conditions became anoxic; micrite was corroded and covered with pyrite. The early micrite (m) in the Sassenfjorden seeps has a moderately depleted carbon isotope signature (−15 to −23‰ VPDB). This is in contrast with other studies (e.g. Campbell et al. (2002)), where the early micrite is the isotopically lightest phase. This may be due to its early precipitation in contact with seawater, in contrast to early cement phases, which nucleated below the seafloor from less diluted seep fluids.

Dolomite has so far only been found inside peloids. Although detailed geochemical studies of Sassenfjorden seeps are still in progress, it is likely that this dolomite was formed by localized bacterial fermentation of organic matter below the sulfate reduction zone. Sulfates, which are dolomite inhibitors, are totally reduced by bacteria in the sulfate reduction zone and are therefore absent below this zone, allowing dolomite precipitation inside fermenting organic-rich peloids (Baker and Kastner, 1981; Stakes et al., 1999).

At a later stage the hardgrounds were colonized by macrobenthos, concurrent with the formation of authigenic fibrous and botryoidal

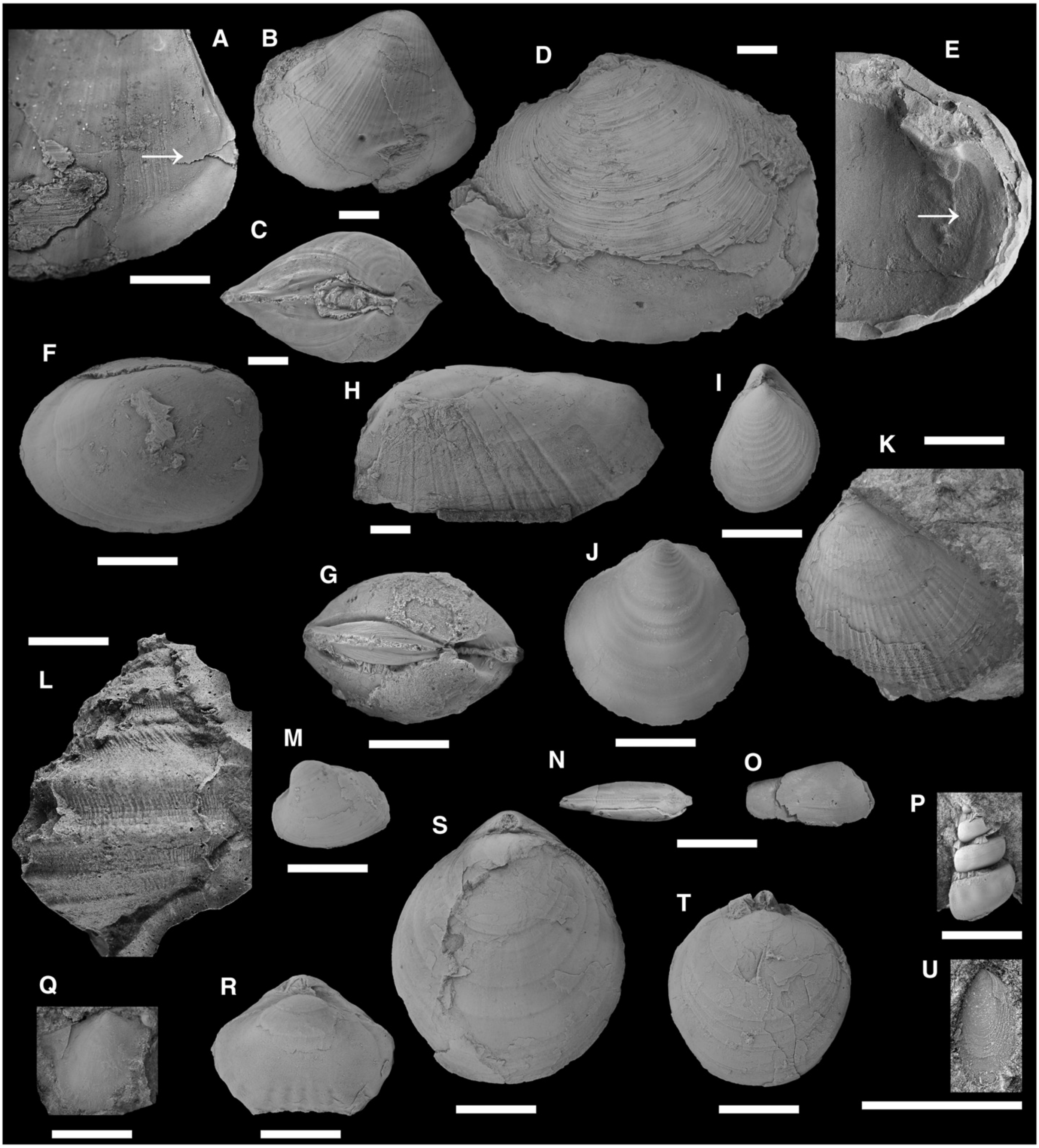

Fig. 7. Representative taxa from the Sassenfjorden seep fauna. All scale bars 1 cm. Specimens deposited in the paleontological collections of the Natural History Museum, University of Oslo (PMO). A: *Thyasira* sp., right valve, with anterior adductor muscle scar indicated by arrow; PMO 217.172. B: *Thyasira* sp., right valve; PMO 217.172. C: *Thyasira* sp., dorsal view of articulated specimen; PMO 217.215. D: Lucinid sp., left valve; PMO 217.169. E: Lucinid sp., silicone rubber cast of left valve internal mold, with anterior adductor muscle scar indicated by arrow; PMO 217.234. F: *Nucinella* sp., left valve; PMO 217.171. G: *Nucinella* sp., dorsal view of articulated specimen; PMO 217.217. H: Solemyid, right valve; PMO 217.168. I: *Buchia* sp., right valve of articulated specimen; PMO 217.182. J: *Camptonectes* sp., left valve; PMO 217.191. K: *Pseudolimea* sp., left valve; PMO 217.194. L: *Eucyclus* sp., side view of silicone rubber cast; PMO 217.235. M: Arcticid, left valve; PMO 217.192. N: Malletiid sp. 1, dorsal view; PMO 217.229. O: Malletiid sp. 1, right valve; PMO 217.229. P: High-spired gastropod; PMO 217.202. Q: *Oxytoma* sp., right valve; PMO 217.214. R: '*Lacunosella*' sp., brachial valve of articulated specimen; PMO 217.199. S: '*Cyrtothyris*' sp., brachial valve of articulated specimen; PMO 217.198. T: '*Zittelina*' sp., brachial valve of articulated specimen; PMO 217.200. U: *Lingula* sp., pedicle valve; PMO 217.201.

carbonate, cementing shells and covering worm tubes. Wood fragments, belemnites and ammonite shells were incorporated into the fabric, and became protected from later compaction by the early cementation. The botryoidal phases have carbon isotope signatures compatible with a thermogenic, rather than biogenic, organic carbon source (Whiticar, 1999), but the relatively moderate depletion of $\delta^{13}C$ may also be due to mixing with inorganic seawater carbon. The oxygen isotopic range corresponds to precipitation from a fluid with temperature between 45 and 60 °C, but this may have been influenced by late diagenesis and may not represent the temperature of the initial seeping fluids.

The sparite clearly represents a later burial phase. The oxygen isotopes indicate hydrothermal fluids with temperatures up to 130 °C. Some of these late calcite veins may represent hydrofracturing during burial, or may also fill fractures formed during pre-burial brecciation of the carbonate. The recrystallized, originally aragonitic shells of bivalves and ammonites show similar isotopic composition to the sparites. This hydrothermal activity is possibly connected with the High Arctic Large Igneous Province (Maher, 2001). An extensive dyke and sill complex of the Diabasodden Suite is exposed in the study area, largely cutting through the underlying Triassic Bothneheia Formation. Burov et al. (1977) dated different samples from these dolerites to between 71 and 130 Ma, but with large error bars. The nearly normal-marine oxygen isotope compositions of the brachiopod and belemnite fossils from the seep at locality 9 indicate little diagenetic alteration of original calcite.

5.2. Seep fauna: paleoecological, biogeographic and macroevolutionary significance

The Sassenfjorden seeps contain a suite of taxa that one would normally expect from Late Jurassic–Early Cretaceous shelf-related sediments, and, indeed, most of the macrofaunal taxa (at the current state of systematic knowledge) are also found in the surrounding Slottsmøya Member mudstones and/or contemporary Boreal sedimentary sequences from, for example, Milne Land, East Greenland (Fürsich, 1982) and North Siberia (Zakharov, 1966, 1970; Sanin et al., 1984). These taxa can thus be considered ecologically as background fauna, rather than having any special adaptation to the seep environment. However, many of these background taxa occur in considerable abundance in the seeps, compared to the surrounding mudstones. This probably reflects both the increasing availability of hard substrates during the formation of the seeps for attachment by epifaunal taxa, and the enhanced food availability in the seep environment compared to the surrounding sediments, a phenomenon known from modern seeps (e.g. Levin et al. (2000); Dando (2010)).

A small number of Sassenfjorden seep taxa were likely more closely linked to seep biogeochemical processes, particularly the formation of sulfides via anaerobic oxidation of methane, because they belong to groups which have modern representatives that are dependent on sulfide-oxidizing bacterial symbionts for nutrition. These include the possible vestimentiferan worm tubes and the solemyid and lucinid bivalves, and probably *Thyasira*. All known living vestimentiferans, solemyids and lucinids have sulfide-oxidizing bacterial symbionts (Dubilier et al., 2008) and there are representative species at modern and fossil seeps, although they are not restricted to this habitat at the family level (e.g. Taylor and Glover (2006)). These last two points also pertain to the thyasirids. It seems likely that the Sassenfjorden *Thyasira* had symbionts, because although not all modern thyasirids have chemosymbionts (Taylor et al., 2007), most of the larger living species do (Dufour, 2005). It is important to note that while solemyids and the possible vestimentiferan worm tubes are found in six and five of the 15 seeps, respectively, the lucinids and *Thyasira* are only found in the largest seep carbonate (locality 9). This could be due to this seep having a greater flux of hydrocarbons than the other Sassenfjorden seeps. *Nucinella* possibly also belongs to the group of symbiotic taxa in the seeps, because although the metabolism of living *Nucinella* species is poorly known, most being very small and found in poorly sampled deep-water habitats, at least one is now thought to have symbionts (Taylor and Glover, 2010). *Nucinella* has yet to be found in modern seeps, but a large fossil species (*Nucinella gigantea*) is known from Cenomanian–Campanian seeps in Hokkaido, Japan (Amano et al., 2007; Kiel et al., 2008a), and the genus has recently been tentatively identified from Late Triassic seeps in Oregon, USA (Peckmann et al., 2011). The Sassenfjorden seep *Nucinella* specimens are even larger than *N. gigantea*, being up to 31 mm in length, and are therefore currently the largest known representatives of the genus.

The Sassenfjorden seep fauna differs ecologically and taxonomically from deep-water Cenozoic seep communities, whose biomass is dominated by seep-restricted (obligate) animals with chemosymbiotic bacteria, including species of vesicomyid and bathymodiolin bivalves, and vestimentiferans (e.g. Sibuet and Olu (1998); Sahling et al. (2003); Levin (2005); Kiel (2010)). These communities also have few predators, or background fauna, and contain a high diversity of seep obligate gastropods (e.g. provannids and various limpets). The lack of some of these obligate taxa in the Sassenfjorden seep fauna is not surprising as they appeared only later: provannids in the Campanian (Kaim et al., 2009), vesicomyids and bathymodiolins in the Eocene (Squires and Goedert, 1991; Kiel, 2006; Amano and Kiel, 2007). The Sassenfjorden seep fauna also differs from many other Mesozoic seep assemblages from the Jurassic and Cretaceous, particularly from those that are thought to have formed in more deep-water environments. Kiel (2010) suggests that these Mesozoic seeps contain a core of seep obligate taxa of the modiomorphid bivalve *Caspiconcha* (Late Jurassic to Late Cretaceous), and the gastropod genus *Paskentana* (Late Jurassic to Early Cretaceous) and the family Hokkaidoconchidae (Late Jurassic to Late Cretaceous). Further, many early Cretaceous seeps also contain abundant specimens of the obligate brachiopod *Peregrinella* (e.g. Campbell and Bottjer (1995); Sandy (2010)). The Sassenfjorden seep fauna has none of these taxa, and instead has the ecological characteristics of Cenozoic and Mesozoic seep communities from shallow shelf settings (Kiel, 2010), with many background taxa and few, if any, obligates. Seep obligates in the Sassenfjorden seeps are the possible vestimentiferans and, probably, *Nucinella* (see Kiel (2010) for a discussion about the paleoecology of *N. gigantea*). Among contemporary Mesozoic seeps the paleoecological structure of the Sassenfjorden seep fauna compares most closely to that of the Tepee Buttes seeps, which formed in 30–100 m water depth in an epicontinental setting and contain, in addition to the lucinid *Nymphalucina*, many widespread benthic macrofaunal species (up to 30 species/butte), occurring at higher density and of larger individual size than in the surrounding dysoxic Pierre Shale sediments (Kauffman et al., 1996). This paleoecological similarity would seem to support the suggestion of Kiel (2010) that there was a depth related control on the taxonomic and ecological structure of seep communities back to at least the Jurassic (see also Amano et al. (2010)).

The geographically closest Mesozoic seeps to the Sassenfjorden examples are the Albian-aged Ellef Ringnes Island and Prince Patrick Island seeps from the Sverdrup Basin of the Canadian Arctic (Beauchamp and Savard, 1992) and the Barremian-aged Kuhnpasset seeps of Northeast Greenland (Kelly et al., 2000). The Ellef Ringnes Island and Prince Patrick Island seeps are suggested to have formed in less than 400 m water depth in a deep prodelta to shelf environment and contain a benthic fauna of abundant bivalves (*Nucula* and *Grammatodon*), terebratulid brachiopods, trochoid gastropods, and two types of serpulid worm tubes (Beauchamp et al., 1989). These fossil taxa are similar to Early Cretaceous Boreal non-seep assemblages and thus the Ellef Ringnes Island and Prince Patrick Island seeps do not seem to have any obligate taxa, or indeed any with chemosymbiotic bacteria. In contrast, the slightly older Kuhnpasset seeps contain both obligate and chemosymbiotic taxa, in the form of the bivalves *Caspiconcha whithami*, *Cryptolucina kuhnpassetensis* and *Solemya* sp. The Kuhnpasset seeps also have rare gastropods, and nuculanoidean and pectinid (*Propeamussium* sp.) bivalves, which are likely background fauna, but, importantly, lack brachiopods (Kelly et al., 2000).

The lack of obligate brachiopods from the Boreal Mesozoic seeps may be contrasted with the abundance of such brachiopods in Late

Jurassic seeps from California (*Cooperrhynchia*; Sandy and Campbell, 1994). In Early Cretaceous seeps, the large-sized obligate dimerelloid brachiopod *Peregrinella* is common in California, Southeastern France, Eastern Europe, Ukraine and Tibet (Campbell and Bottjer, 1995). As in Svalbard, obligate seep brachiopods are also absent from the Tithonian Gateway Pass seep, Antarctica (Kelly et al., 1995) and the Albian seeps from Hokkaido (e.g. Kiel et al. (2008a)). There could be paleobathymetric elements to this pattern (cf. Kiel (2010)), but alternative explanations might be that: 1) *Peregrinella* and *Cooperrhynchia* had a distribution in seeps that was restricted to the Tethys and the Eastern side of the Panthalassic Ocean during the latest Jurassic to Early Cretaceous; or 2) the Svalbard seeps are stratigraphically intermediate in age between the occurrence of *Cooperrhynchia* (mid to late Tithonian) and *Peregrinella* (Valanginian and younger). The presence of '*Cyrtothyris*', '*Praelongithyris*' and '*Monticlarella*' in the Sassenfjorden seeps indicates paleobiogeographic affinities with NW European and Boreal faunas. This is the most northerly record for '*Monticlarella*', but '*Cyrtothyris*', '*Praelongithyris*' and '*Zittelina*' have been reported from the Early Cretaceous of Greenland (Owen, 1976). '*Lacunosella*' is more typically considered a brachiopod found along the margins of Tethys in the Late Jurassic (Khudolej and Prozorovskaya, 1985; Sandy, 1988; Voros, 1993) and into the Early Cretaceous (Smirnova, 1984, discussed in Manceñido (2002)), but has also been recorded from the Early Cretaceous of Greenland (Owen, 1976; Harper et al., 2005). Similarly '*Zittelina*' is typically considered to have a Tethyan to NW European distribution.

Three additional features of the Sassenfjorden seep assemblages are of note. First, in spite of their Boreal position, the number of Sassenfjorden brachiopod genera is the highest known from any seep and this is the first hydrocarbon seep setting that has yielded brachiopods from more than one brachiopod order (in this case Lingulida, Terebratulida and Rhynchonellida). Second, the Sassenfjorden seeps also provide the first record of *Lingula* from this environment, although it is worth noting that a lingulid (*Pyrodiscus*) has been described from Silurian hydrothermal vents of the southern Ural Mountains of Russia (Little et al., 1999). Third, the Sassenfjorden carbonates host not only the earliest occurrence of *Thyasira* at seeps, but also the oldest known record of this bivalve family anywhere, with the previously recorded oldest species being known from the Albian of England (Taylor et al., 2007) and Japan (Kiel et al., 2008a), and the Valanginian–Hauterivian of the French Alps and Carpathians (Kiel et al., 2008a).

5.3. Hydrocarbon source and migration

An obvious candidate source for the hydrocarbons that formed the Sassenfjorden seeps is the Agardhfjellet Formation itself. The upper 100 m generally have TOC below 5%, but this increases to up to 12% in the underlying mudstones of the formation. Other, deeper potential source rocks include the black shales of the Middle Triassic Botneheia Formation, ca. 500 m stratigraphically below the Slottsmøya Member, with TOC reaching 10%. With a normal geothermal gradient, such relatively shallow sources would imply a biogenic production of methane. The carbon isotope values observed in the seeps are not fully in the biogenic range, but this may be due to mixing with heavier inorganic seawater carbonate. Alternatively, a thermogenic source can be envisaged in e.g. Carboniferous coals of the Billefjorden Group (Cutbill et al., 1976).

Several other Mesozoic hydrocarbon seeps are associated with synsedimentary faults or are situated on convergent margins (e.g. Kelly et al. (2000); Campbell et al. (2002)). Such faults could have provided pathways for upwards migrating hydrocarbons. There is little evidence of synsedimentary tectonic activity in the Mesozoic along the Billefjorden Fault Zone, which is situated to the east of the Sassenfjorden seeps (Haremo et al., 1990), and we have so far not observed any direct evidence of synsedimentary faults in the study area.

The occurrence of the Sassenfjorden seeps can possibly be correlated with several important events near the Volgian–Ryazanian boundary. Firstly, the uppermost Slottsmøya Member is associated with shallowing (Nagy et al., 1988). The resulting pressure drop may have allowed the release of gas hydrates (cf. Kiel (2009)), although the stability of hydrates would require fairly large water depth (>500 m) and/or a very shallow geothermal gradient. Secondly, although the timing is uncertain (e.g. Maher (2001)), early manifestations of the High Arctic Large Igneous Province may have started already at the time of seepage, possibly leading to a steeper geothermal gradient, shallow-depth thermogenic methane production and mobilization of hydrocarbons and hydrothermal activity. The extensional tectonic setting would also be conducive to seismicity.

The Sassenfjorden seeps are situated slightly below the Mjølnir impact event (Gudlaugsson, 1993; Dypvik et al., 1996; Smelror et al., 2001), making any connection unlikely. Tsikalas et al. (1998) estimated that the Mjølnir impact, placed ca. 400 km from the Janusfjellet section, had an energy corresponding to a magnitude 8.3 earthquake. Dypvik et al. (2006) reported an iridium enrichment 4.3 m below the Myklegardfjellet Bed in their section at Janusfjellet. This places the Sassenfjorden seeps 0.7–6.7 m below the iridium anomaly, which is a considerable vertical distance even considering the possibility that the seeps were situated in pockmarks. In addition, the presence of both Volgian and Ryazanian ammonites in the seeps indicates a prolonged phase or several distinct episodes of seepage, which is difficult to reconcile with a single catastrophic event.

6. Conclusions

The Sassenfjorden carbonate bodies represent the first discovery of fossil cold seeps in Svalbard. The abundance, diversity and three-dimensional preservation of the seep invertebrate fauna, particularly the brachiopods, open a new window on the High Boreal marine ecosystems near the Jurassic–Cretaceous boundary in general, and also widens the spectrum of previously known Mesozoic seep associations. The Sassenfjorden seeps differ from many previously known Mesozoic seeps in their relatively high diversity but few, if any obligate seep taxa. These unusual aspects may be connected with relatively shallow water during their formation. The triggering mechanism for seepage at the stratigraphic level of the seeps remains unknown, but may have involved a drop in sea level, seismicity or steepening of the geothermal gradient in early phases of the High Arctic Large Igneous Province.

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