

Tasmanites algae—contributors to the Middle Triassic hydrocarbon source rocks of Svalbard and the Barents Shelf

Jorunn O. Vigran,¹ Atle Mørk,^{1,2} Arne W. Forsberg,³ Hermann M. Weiss¹ & Wolfgang Weitschat⁴

1 SINTEF Petroleum Research, NO-7465 Trondheim, Norway

2 Department of Geology and Mineral Resources Engineering, Norwegian University of Sciences and Technology, NO-7491 Trondheim, Norway

3 StatoilHydro ASA, NO-0246 Oslo, Norway

4 Geological–Paleontological Institute, University of Hamburg, Bundesstrasse 55, DE-20146 Hamburg, Germany

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Correspondence

Jorunn O. Vigran, SINTEF Petroleum Research, NO-7465 Trondheim, Norway.
E-mail: jorunn.vigran@sintef.no

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Abstract

When moving from west to east across Svalbard, organic geochemical, palynological and sedimentological data from the Middle Triassic dark shales of the Sassendalen Group show an improved quality of hydrocarbon source rock (kerogen type II/III), and an increased abundance of structured algal material, including *Tasmanites*. Triassic specimens of *Tasmanites* in palynological residues from Svalbard are generally of small size (<100 µm in diameter). *Tasmanites* of variable size, and the associated degradation products, occur frequently in Middle Triassic dark shales, and extraordinarily large-sized specimens (phycomata >500 µm in diameter) are recorded in silty shales and siltstones palynologically dated as being of Ladinian–Carnian age. Similar occurrences are also present in deposits of the Norwegian Barents Sea. Our organic geochemical analyses suggest that *Tasmanites* is a major source for the hydrocarbons encountered in these rocks. *Tasmanites* algae are also enriched in Ladinian–Norian deposits in Taimyr, Siberia. The development of a marine embayment, the direction of the ocean currents, the supply of clastic material and freshwater, and the palaeolatitude all show similarities to the conditions in the present Mediterranean, and adjacent Atlantic Ocean. Ecological conditions in the water column (light intensity, nutrient supply and temperature) are expected to have been similar, and favoured the growth and accumulation of *Tasmanites*. The accumulation of monotypic, large *Tasmanites* cells in silty shales is explained as a result of contemporaneous recirculation and sorting.

The organic-rich Mesozoic deposits in Svalbard and the Barents Shelf are of major interest for hydrocarbon exploration in the Norwegian Arctic (Leith et al. 1992). The Triassic deposits in Svalbard have been extensively studied (Buchan et al. 1965; Lock et al. 1978; Mørk et al. 1982; Mørk et al. 1999; Krajewski et al. 2007), and systematic sampling spread stratigraphically and regionally has been carried out. The corresponding Triassic subgroups on the Barents Shelf have been the object of shallow stratigraphic drilling programs at IKU/SINTEF Petroleum Research (Mørk et al. 1992; Vigran et al. 1998) and the Norwegian Petroleum Directorate (Riis et al. 2008 [this issue]). Systematic sampling has also been carried out in all shallow stratigraphic cores from the Barents Sea.

Middle Triassic strata contain excellent hydrocarbon source rocks throughout the Arctic realm, including

Svalbard. The palaeogeographical reconstruction for the Middle Triassic (Fig. 1) indicates that sediments are mainly derived from the west, with coastal sediments formed along western Spitsbergen (Bravaisberget Formation), and with generally lower sedimentation rates eastwards in Svalbard (Botneheia Formation). The diverse ammonoid faunas of the Lower and Middle Triassic Sassendalen Group (Tozer & Parker 1968; Weitschat & Lehmann 1983; Weitschat & Dagys 1989; Mørk et al. 1992; Dagys & Weitschat 1993; Dagys et al. 1993) allow accurate dating, thereby supporting detailed palynological results (Vigran et al. 1998). The Middle Triassic succession forms a single, major transgressive–regressive sequence in Svalbard and the Barents Sea (Mørk et al. 1982; Mørk et al. 1989). This high-order sequence can be traced throughout the Arctic (Mørk &

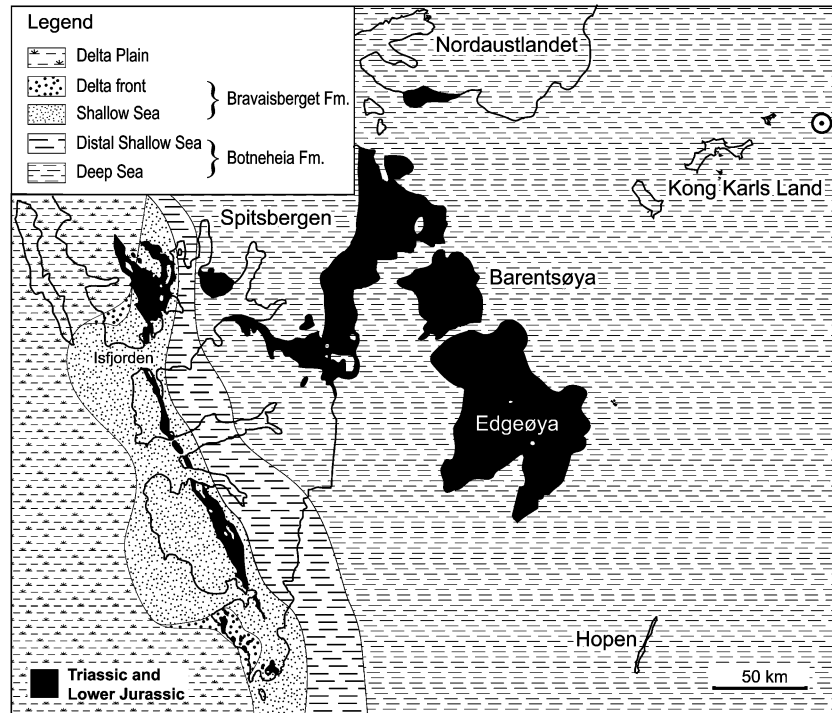


Fig. 1 Exposures of Triassic rocks (black): the facies distribution is shown with different shading (see legend in figure). The circle north-east of Kong Karls Land marks the location of the cores containing *Tasmanites*.

Smelror 2001), to the Canadian Arctic Islands and Alaska (Embry 1989), and to East Siberia (Egorov & Mørk 2000), and the sequence may be regarded as global in nature (Embry 1997).

Following the early Anisian transgression in Svalbard, dark organic-rich shales were deposited throughout the islands. The thick deposits of the Bravaisberget Formation in the western area agree with high sedimentation rates according to a position close to a palaeocoast in the north-west. In the east, the upper part of the Botneheia Formation, the Blanknuten Member (Mørk et al. 1999), previously called the “oil shale unit” by Falcon (1928), is very rich in organic material (Mørk & Bjorøy 1984), and represents distal shelf sedimentation (Mørk et al. 1982; Leith et al. 1992; Krajewski 2000). Slow clastic sedimentation and periodic low oxygen levels resulted in recurrent anoxic bottom conditions, which preserved as much as 10% of the organic matter in the rock (Mørk & Bjorøy 1984; Krajewski 2000). Moving from west to east, the source-rock potential improves in Svalbard (Mørk & Bjorøy 1984), and this trend may continue into the Barents Shelf (Leith et al. 1992; Mørk & Elvebakk 1999; Riis et al. 2008). Here, we present evidence that abundant *Tasmanites* algae, seen macroscopically and in palynological residues from this organic-rich succession, are the major source for the hydrocarbons encountered. Based on our observations, we aim to answer the following questions. What influenced the repeated *Tasmanites*

blooms of the Barents Shelf during the Middle Triassic? Which conditions favoured the deposition, enrichment and preservation of the *Tasmanites* cells on the sea bottom?

Occurrences of *Tasmanites*

Prasinophycean algae currently occur in abundance in the Mediterranean and in the Bay of Biscay, and algal blooms regularly occur in the British Channel (Parke 1966; Parke et al. 1978). The well-described life cycle of recent and fossil prasinophycean algae (Parke & den Hartog-Adams 1965; Parke 1966; Boalch & Parke 1971; Parke et al. 1978; Guy-Ohlson 1988) may be summarized as follows: prasinophycean algae may originate as very small motile cells (10 µm in diameter) in the Mediterranean and in the Bay of Biscay. As nonmotile phycmata, they float passively through the Bay of Biscay, northwards into the Atlantic Ocean, while their cavity size and wall thickness multiplies during a relatively short period of time. The assimilating, light-dependent phycmata have the ability to move vertically, daily from about 10 m in depth down to 100 m in depth (i.e., below the photic zone). Their presence in the water column is believed to be restricted by high water temperatures (Parke & den Hartog-Adams 1965). Ackmann et al. (1970) suggested that the recent prasinophycean algal blooms were related to enrichment of the water by nitrogen and phosphates.

Enrichment of *Tasmanites* in Palaeozoic deposits from Gondwana have, on the other hand, been interpreted as reflecting algal blooms in areas supplied with meltwater from surrounding glaciers (Revill et al. 1994).

The morphology and chemistry of recent, mature prasinophycean phycomata show that the walls are lipid-rich, with radial elements of fatty acids and some silica, and that they have an internal pectinid layer (Christensen 1966; Jux 1968, 1969; Kjellström 1968). The mature phycoma opens by a simple slit (Parke et al. 1978), as did the fossil *Tasmanites* cysts (Guy-Ohlson 1988).

Palynological results

Palynological investigations of Triassic rocks from Svalbard and the Barents Shelf (Hochuli et al. 1989; Mørk et al. 1990; Mangerud & Rømuld 1991; Mørk et al. 1992; Vigran et al. 1998) describe variably well-preserved organic material, and palynological associations of variable diversity. These publications are all based on organic residues obtained through the standard processing techniques of the IKU/SINTEF Petroleum Research laboratory. The processing included sieving (with 200- and 10- μm meshes), and so only small- and medium-sized particles remain in the residues. The present paper summarizes data concerning the presence and abundance of *Tasmanites* and other plankton, extracted from about 40 distribution charts showing the palynology of sections in Svalbard and stratigraphic cores from the Barents Shelf. This work is being published elsewhere by Vigran and co-workers.

The palynological residues indicate that in Svalbard there is an eastwards enrichment of varied plankton, including *Tasmanites* and its degradation products. Small-sized *Tasmanites* cells appear regularly in residues from marine deposits throughout the Triassic succession in Svalbard (Fig. 2) and the Barents Shelf (Fig. 3c, d), and may be abundant in the Spathian–Ladinian deposits of the Sassendalen Group. Larger *Tasmanites* cells are represented only by wall fragments, even when observed as dark dots (approximately 0.5–0.6 mm in diameter) on weathered surfaces, and in thin sections of siltstones from the Botneheia Formation.

At Torellneset, the south-westernmost point of Nord-austlandet, loose blocks of grey, silty mudstones have surfaces dominated by macroscopic *Tasmanites* cells (Fig. 4a, b). The silty blocks in the field appear in screes, together with dark grey shales, free of visible algal or faunal remains, and eroded phosphatic pebbles. The latter contain a rich ammonoid fauna dated by Tozer (1973) to be of Spathian and Anisian ages.

Samples of grey, silty mudstone and dark shale were palynologically analysed for the study presented in this

paper. Dark-grey shales were crushed and treated in the laboratory with HCl-HF-HCl. After the treatment with acids, the residues were treated ultrasonically, followed by a brief oxidation by nitric acid to disintegrate the degraded organic material sticking to the palynomorphs. The remaining residues contain a generally poorly preserved, low-diversity palynomorph association dominated by small-sized *Tasmanites* (with diameters of about 50 μm), strongly degraded wall fragments of *Tasmanites* and abundant *Micrhystridium*, *Vitreisporites* spp. and indeterminate bisaccate pollen. The record of *Paracirculina tenebrosa* Scheuring, 1970 and *Triadispora aurea* Scheuring, 1970, which are represented in upper Ladinian (Langobardian) and Carnian (Cordevolian) deposits of the Germanic and Alpine Triassic (Scheuring 1970, 1978) confidently date the dark shales as younger than the ammonoid dated rocks from the same locality.

The grey silty shales from Torellneset contain monotypic assemblages of large, moderately flattened *Tasmanites* cells (phycomata), 500–600 μm in diameter, and with slit-like wall openings. The thick walls, 80–100 μm , have radial elements and evenly spaced pores, as shown by scanning electron microscope micrographs (Fig. 4c–e). The algae may be assigned to the similarly sized Devonian species *Tasmanites punctatus* Newton, 1875, in which the wall thickness never approaches 100 μm (Winslow 1962: 80–81, fig. 10).

Samples of the grey, silty mudstone were given the same chemical treatment as the dark shales. Variably sized *Tasmanites*, estimated as having diameters of 50–600 μm , dominate the isolated organic matter. The surface structures of the large specimens agree with the structures of the spheres observed on rock surfaces and in thin sections of rock specimens. In addition, the organic residues comprise fine particulate material, mostly as fairly dense, spongy, granular aggregates or sheet-like material embedding variably well-preserved palynomorphs. Compared with the dark-grey shales, the organic material of the siltstone residues is structurally better preserved, and contains a slightly more diverse and stratigraphically significant palynomorph association. *Fossapollenites moderatus* Scheuring, 1970, *Infernopollenites* spp., *P. tenebrosa*, *T. aurea*, *Vitreisporites* sp. and abundant *Micrhystridium* spp. represent late Ladinian and Carnian evidence in the Alpine and Germanic Triassic (Scheuring 1970, 1978). In Svalbard, this association has its earliest record in the Ladinian deposits in the highest part of the Sassendalen Group.

The presence of *Ricciisporites* sp. and cf. *Ricciisporites tuberculatus* Lundblad, 1954 in the association from Nord-austlandet is noteworthy: the stratigraphically oldest occurrence of the genus in the Alpine and Germanic Triassic is in the latest Middle Keuper, late Norian

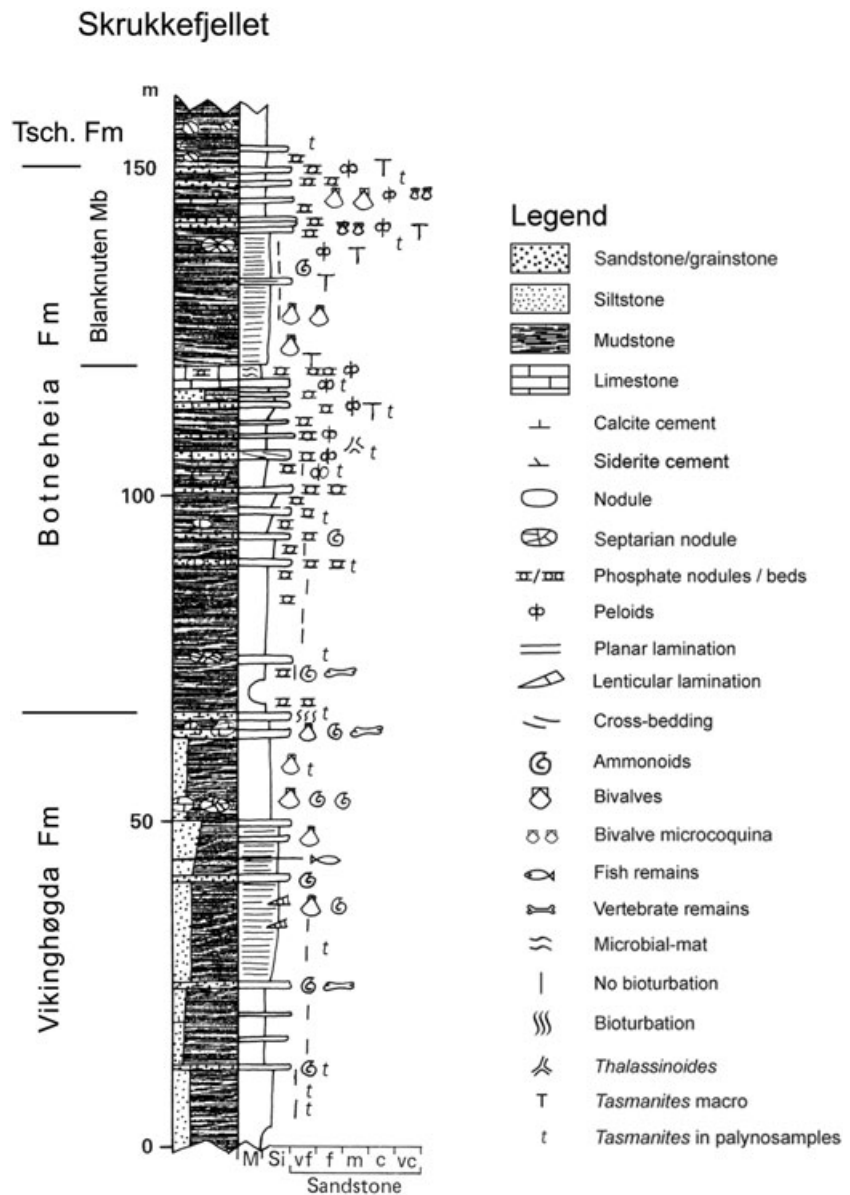


Fig. 2 The uppermost Lower Triassic of the Vikinghøgda Formation and the Middle Triassic of the Botneheia Formation, with the occurrences of *Tasmanites* in palynological slides (t), and in thin sections (T); Tsch. Fm., Tschermakfjellet Formation. The Skrukkefjellet section is on northern Edgeøya.

assemblage GTr17 (Heunisch 1999). Elsewhere in Svalbard the oldest records of *R. tuberculatus* are in the Carnian deposits of the Tschermakfjellet or De Geerdalen formations, and on the Barents Shelf it occurs in the Carnian–Norian deposits highest in the Snadd Formation. This palynological evidence, to be published elsewhere by Vigran et al., indicates that the genus *Riccisporites* appears in Carnian Arctic deposits earlier than in the Germanic realm. The evidence also suggests that the grey, silty mudstones and the dark shales from Torellneset in eastern Svalbard represent deposits formed during the late Ladinian–Carnian.

Colour tone, light refractive index and translucency of the sheet-like material dominating the organic-rich

residues from the Torellneset dark shales are different from those of the structured algal material from the siltstones, despite the fact that they may have the same burial history. If the rocks had represented deposits from geographically separated localities, they might have been evaluated as representing different stages of maturity.

An unusually rich occurrence of *Tasmanites* in the mudstones of late Ladinian age, similar to the one in Svalbard, has recently been recovered from a stratigraphic core drilled in the sea north-east of Kong Karls Land (Fig. 5; Riis et al. 2008). Layers rich in *Tasmanites* also occur in East Siberia (Fig. 6), where the Triassic succession closely resembles that on Svalbard (Egorov & Mørk 2000). The deposits in East Siberia are of late

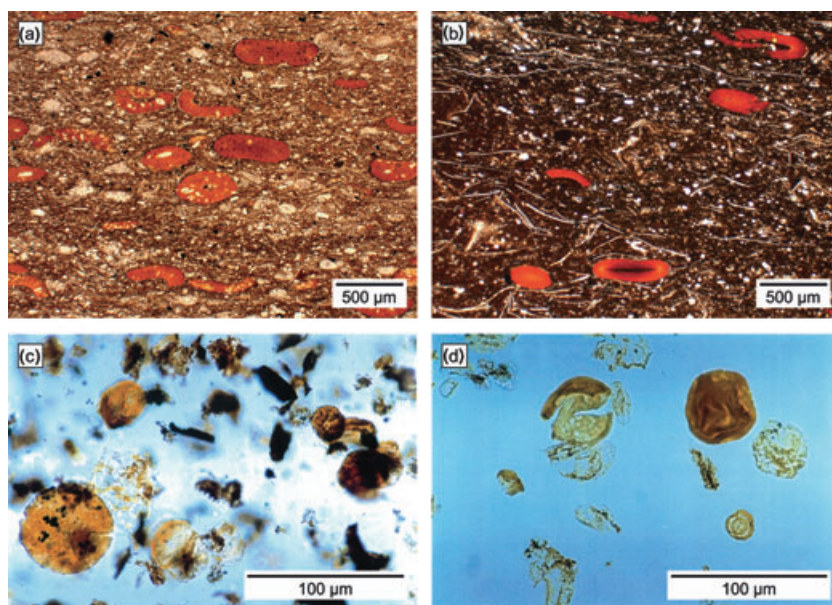


Fig. 3 (a) Flattened and fragmented *Tasmanites* cells, together with siltstone grains. Thin section: Botneheia Formation at Sticky Keep (STK1-509), central Spitsbergen. (b) Flattened and fragmented *Tasmanites*, together with bivalve microcoquina shells and silt grains, in an organic- and phosphate-rich matrix. Thin section: Trehøgdene, Botneheia Formation (TRH-225), central Spitsbergen. (c) Small *Tasmanites* cell from a palynological residue; organic debris stick to and hide other plankton. Sample from the Botneheia Formation, from Skrukkefjellet, Edgeøya (SKR2 119.0 m). (d) *Tasmanites* in cleaned (oxidized) residue, together with poorly preserved marine and terrestrial palynomorphs. Sample from Late Olenekian (Spathian) mudstone, core 7323/07-U-03 (131.7 m) from the Barents Sea.

Ladinian and Norian age, and the *Tasmanites* specimens appear to be morphologically identical to those from Torellneset.

Thin sections of siltstones from localities widespread in Svalbard (see the sedimentological sections in Mørk et al. 1982) show that large *Tasmanites* cells may be abundant, and are often associated with peloids and bivalve microcoquina associations (Fig. 3a, b). These finds are most abundant in silty or pellet-rich beds from the upper part of the Botneheia Formation. Beds without traces of bioturbation contain masses of thin-walled (<1 mm in diameter) bivalve shells. The same beds often contain *Tasmanites* cells of fairly uniform diameters (500–600 µm), and with simple slit-like openings (Figs. 3a, 4b, 5a), as in the Siberian specimens (Fig. 6b, c). The pellets of such beds are often phosphatized. This part of the succession is also dominated by the *Thalassinoides* ichnofacies, indicating fluctuations between anoxic and oxic periods, where the influx of oxygenated water by storms enabled quick colonization by *Thalassinoides* within a dominantly anoxic environment (Mørk & Bromley 2008, this issue).

Hydrocarbon source-rock potential of beds containing *Tasmanites*

Two samples from both lithologies at Torellneset were analysed by Rock-Eval pyrolysis (Espitalié et al. 1977) to determine their hydrocarbon source potentials. In addition, a concentrate of *Tasmanites* algae was prepared by HCl and HF acid treatment of the *Tasmanites*-containing sample, and by the subsequent sieving of the organic

residue through a 500-µm grid, keeping the >500-µm residue. This concentrate was also subjected to Rock-Eval pyrolysis (Table 1). The analyses show that the dark-grey shale can be classified as a type-II source rock (Fig. 7), whereas the grey, silty mudstone containing *Tasmanites* can be classified as a mix of type-II and type-I sources. Not surprisingly, the *Tasmanites* concentrate is classified as a type-I source with an excellent hydrocarbon-generative potential—reaching a staggering 900 mg of hydrocarbons per gram of organic carbon (Table 1; Fig. 7). Similar values have been reported from Tasmanian *Tasmanites* (Reville et al. 1994).

Hydrocarbon generation kinetics of beds containing *Tasmanites*

The temperature at which the highest pyrolysis yield is obtained (T_{max}) varies in a systematic manner among the sample types described above (Table 1; Fig. 7). Whereas the dark-grey shales reach a maximum yield at 427–430°C, suggesting thermal immaturity, the T_{max} values of the grey shales containing *Tasmanites* are 16–19°C higher (446–449°C), and the *Tasmanites* concentrate needs an additional 6–9°C before maximum pyrolysis yield is reached (455°C). All samples, however, show production index values of not more than 0.04, which indicates that none of them have generated significant concentrations of liquid hydrocarbons, and that all samples, consisting of scree material derived from a small area, are considered to represent the same locality. The differences in T_{max} , therefore, can hardly be attributed to differences in maturity, but rather to different

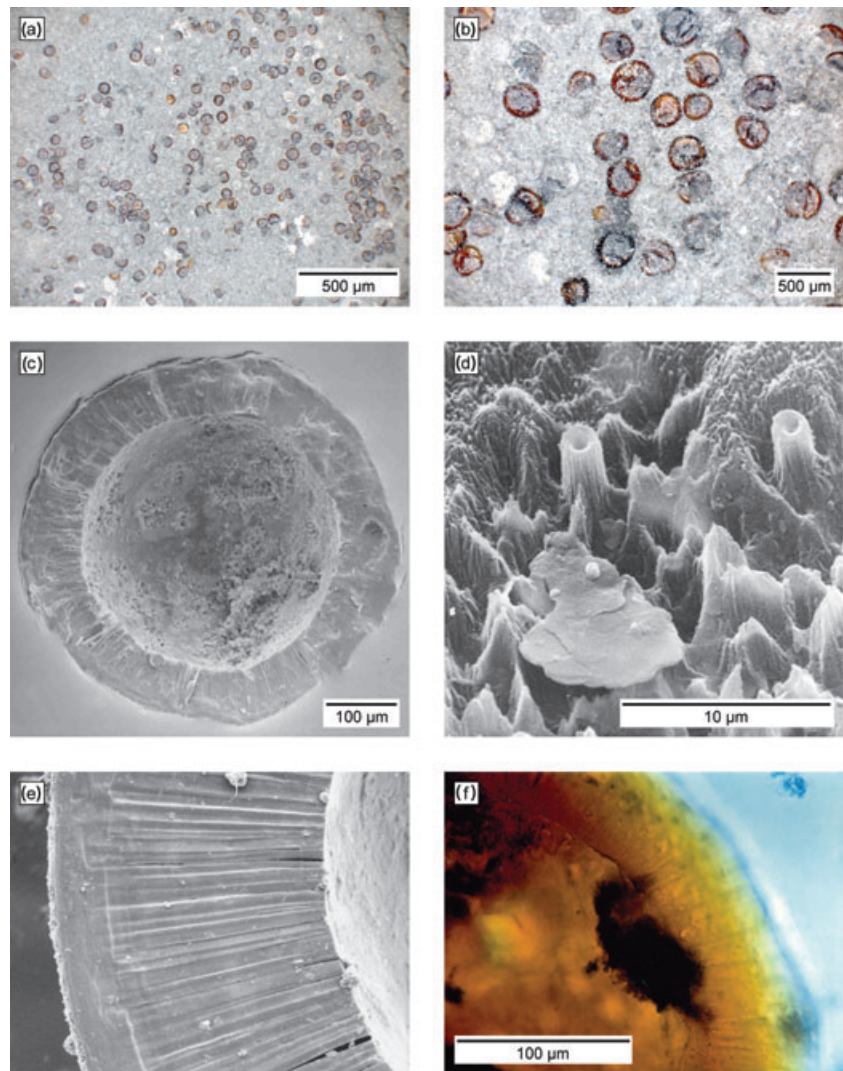


Fig. 4 Occurrences of *Tasmanites* at Torellneset on Nordaustlandet. (a, b) Abundant *Tasmanites* at a siltstone surface. (c) Scanning electron microscope picture showing the inner cavity of a split specimen of *Tasmanites*. Note the pore structure and the eroded areas. (d) Details of interior pores, where the wall surrounding the pores is more resistant to erosion than the embedding tissue. (e) Wall structure of a *Tasmanites* cell showing the outer lamellar and the inner radial wall structure. (f) *Tasmanites* wall structure in transmitted light.

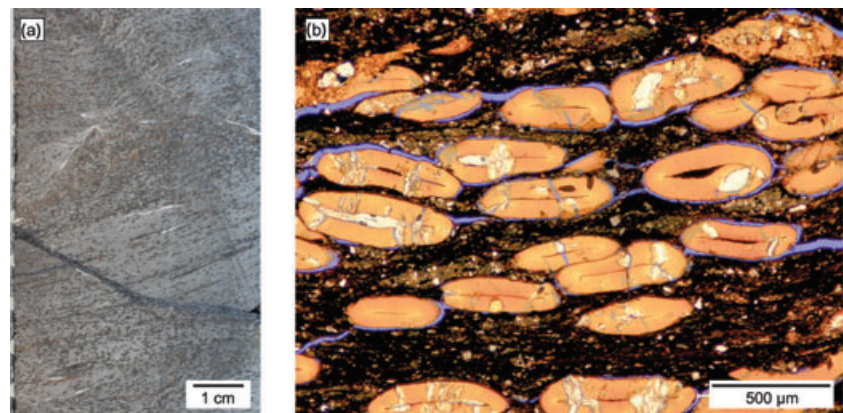


Fig. 5 *Tasmanites* occurrences from a stratigraphic core drilled east of Kong Karls Land (Fig. 1). (a) Vertically cut core sample with rock-forming abundances of *Tasmanites* (brownish specks). (b) Thin section (transmitted light) from the same sample showing the dense packing of *Tasmanites* cells.

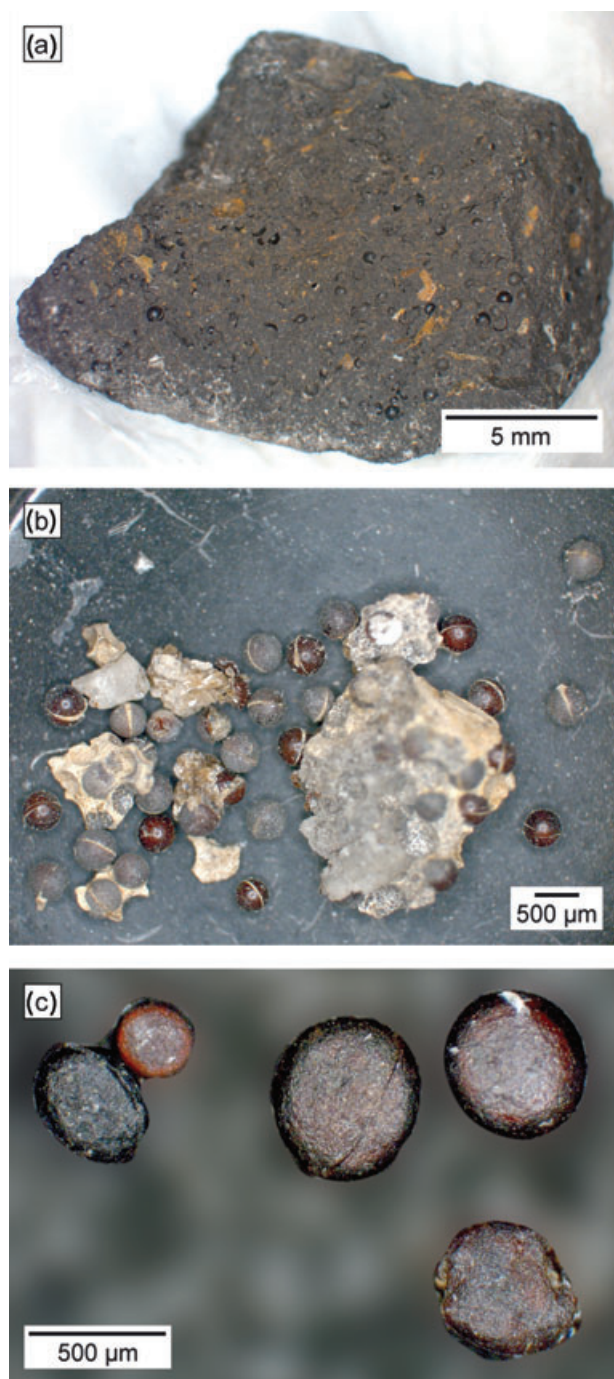


Fig. 6 (a) *Tasmanites* in a rock sample of Early Ladinian age, from Djugulak River in the Kolymna River Basin, east Siberia. (b) *Tasmanites* in a rock sample of Early Ladinian age, from Olenek River, north-east Siberia. Note the simple slits splitting the cells. (c) Single *Tasmanites* cells, Lower Norian, from Buur Basin, East Siberia.

kinetic properties. Similar observations have been made on tasmanite seams, associated siltstones and *Tasmanites* fossil concentrates from Tasmania, Australia (Revill et al. 1994: table 2).

The data presented above (Table 1; Fig. 7a, b) suggest that a fairly organic-rich (total organic carbon content [TOC] ca. 8%) mudstone can be regarded as the general background deposit in the Middle–Upper Triassic succession at this location. The deposition of a marine organic facies containing type-II kerogen agrees well with findings in contemporaneous sediments elsewhere in the Svalbard Archipelago (Mørk & Bjorøy 1984). The presence of a significant proportion of macroscopic *Tasmanites* algae enhances the carbon-normalized hydrocarbon potential significantly, but also changes the kinetic properties of the source rock. This is important to take into consideration when performing numerical simulations, i.e., petroleum system modelling and basin modelling, with the mid-Triassic source rock. To shed some light on the kinetic properties of the mudstone containing macroscopic *Tasmanites* algae, a sample was analysed by non-isothermal, open-system pyrolysis. The activation energy distribution (Table 2) is quite narrow, and the transformation curve for a geological heating rate of 3 K My^{-1} (Fig. 8a) is rather similar to that of Eocene Green River shale (10 replicate analyses of one homogenized sample, data from Peters et al. 2006), the prototype of a type-I source rock, but is less steep than that of the sample of tasmanite from Tasmania (data from Revill et al. 1994). The temperatures at 50% conversion (T_{50}) of all of these rocks are, however, very similar (148–151°C).

Figure 8(b) compares the transformation curves of the Torellneset sample and the Tasmanian tasmanite with those of 52 thermally immature samples from the Jurassic Oxford Clay, which is regarded as a typical marine type-II source rock (Peters et al. 2006). The Oxford Clay curves show a wide spread of transformation temperatures ($T_{50} = 134\text{--}156^\circ\text{C}$, with one outlier at 162°C), and generally a lesser slope, which reflects both local variations in kerogen composition (hydrogen index, $HI = 255\text{--}774 \text{ mg g}^{-1} \text{ TOC}$) and the more heterogeneous nature of the type-II kerogen structure. Although the mid-Triassic, *Tasmanites*-rich silty sample from Torellneset does not plot distinctly outside the Oxford Clay population, it does start generating hydrocarbons at significantly (ca. 15°C) higher temperature than the average Oxford Clay. Once started, kerogen transformation occurs rather quickly, and ends at similar temperatures as for the Oxford Clay. All of this is consistent with the contribution from the *Tasmanites* algae to the “background” type-II kerogen of this sample.

Discussion

The green alga *Tasmanites* occurs throughout the Triassic succession of Svalbard and the Barents Shelf. Variably-sized cells are regularly recorded in palynological samples, particularly in fine-grained mudstones that

Table 1 Total organic carbon content and Rock-Eval pyrolysis results of the samples analysed (mean values).

Sample	TOC wt %	S_1	S_2	S_3	PI	HI	OI	T_{max} °C
		mg HC g rock	mg HC g rock	mg CO ₂ g rock	S_1	mg HC g TOC	mg HC g TOC	
A	61.4	2.59	553.0	1.2	0.00	901	2	455
B1	8.2	0.42	50.8	0.6	0.01	620	7	446
B2	8.0	0.48	50.0	1.3	0.01	625	16	449
B3	7.1	0.99	41.67	1.0	0.02	587	14	436
C1	13.2	2.47	66.8	1.9	0.04	506	14	430
C2	11.0	2.18	56.9	1.6	0.04	517	15	427

Samples: A, *Tasmanites* concentrate; B1–B3, whole rock with *Tasmanites* (grey, silty, dark shale); C1 and C2, whole rock without *Tasmanites* (dark-grey shale). Sample B3 was analysed in 2007, and the remaining samples were analysed in 1984.

Abbreviations: TOC, total organic carbon; S_1 , thermally extracted hydrocarbons; S_2 , hydrocarbons formed during pyrolysis; S_3 , carbon dioxide formed during pyrolysis at temperatures below 390°C; HI , hydrogen index ($100 \times S_2/TOC$); OI , oxygen index ($100 \times S_3/TOC$); PI , production index ($S_1/(S_1 + S_2)$); T_{max} , temperature at which the highest pyrolysis yield is obtained.

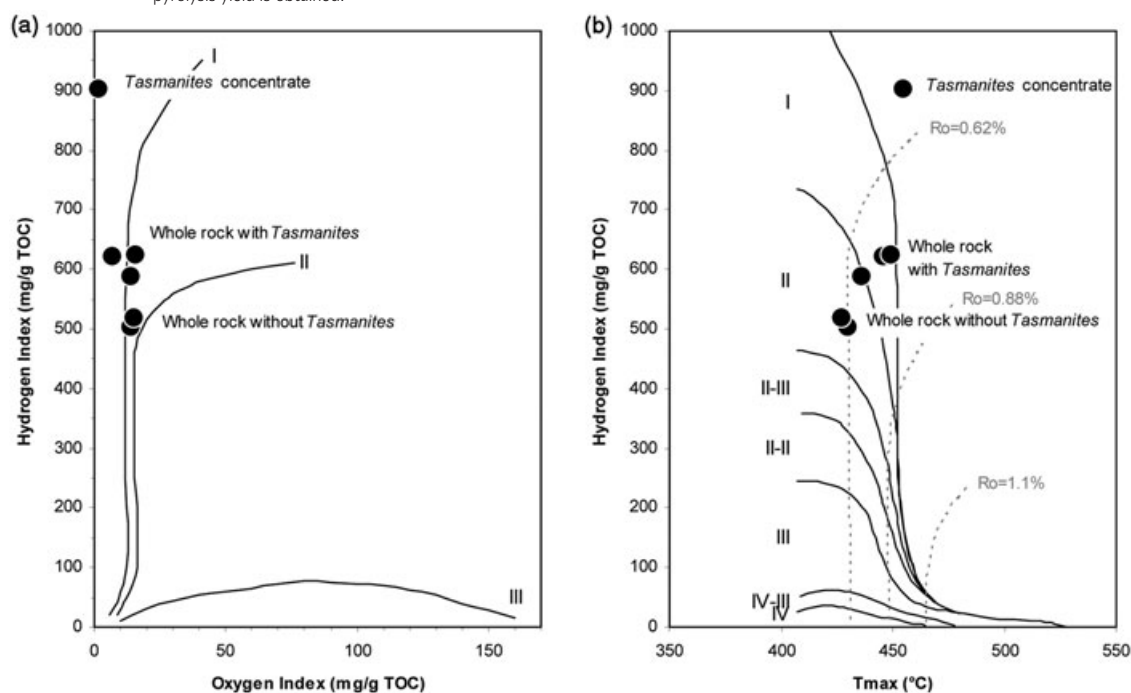


Fig. 7 Differences between Rock-Eval pyrolysis results of *Tasmanites* algae (type I) and matrix kerogen (type II), illustrated in (a) a modified van Krevelen diagram, and (b) a hydrogen index (HI) vs. temperature at which the highest pyrolysis yield is obtained (T_{max}) plot. The latter also illustrates the relatively low maturity of the samples from the Torellneset locality.

occur throughout the succession. Well-defined large *Tasmanites* cysts may be concentrated and dominate coarser grained lithologies, such as siltstone and peloid sandstones. The cells are seen as opened spheres, reflecting that the living content had been shed prior to their final deposition.

In the late Middle Triassic succession, the beds containing *Tasmanites* occur together with bivalve microcoquina layers, reflecting mass mortality caused by low oxygen levels at the time of deposition (Mørk & Bromley 2008).

Pelagic juvenile bivalve larvae, when starting to grow shells, may have settled on the anoxic sea bottom to form death assemblages. The anoxic conditions causing the mass mortality and the formation of layers enriched in bivalve microcoquina were probably connected with periodic algal blooms, when masses of plankton were concentrated closer to the surface, and later left emptied cysts on the sea bottom.

Interbeds of strongly bioturbated layers, mainly containing the tunnel-forming trace fossil *Thalassinoides*,

Table 2 Frequency factor (A), activation energy (E_a) distribution, and temperatures for 10, 50 and 90% transformation at a geological heating rate of 2 K My^{-1} for the sample from Torellneset (B3 in Table 1).

$A \text{ s}^{-1}$	$E_a \text{ kcal mol}^{-1}$	Potential mass %	Transformation mass %	$T \text{ }^\circ\text{C}$
1.83E+14	44	0.23	10	128
	45	0.14	50	148
	46	0.38	90	164
	47	0.43		
	48	0.39		
	49	1.12		
	50	0.02		
	51	0.87		
	52	4.21		
	53	12.65		
	54	9.73		
	55	48.2		
	56	10.62		
	57	5.58		
	58	1.84		
	59	2.64		
	60	0		
	61	0		
	62	0.95		

demonstrate periodic oxic excursions. It seems reasonable to suspect that the co-appearance of bivalve-microcoquina, phosphatic pellets and dominant large *Tasmanites* cells results from mechanical sorting, a conclusion supported by the occurrence of current ripples in some of these laminated siltstone beds. The sorting and redeposition, together with coarser lithologies were probably caused by a storm or current mechanism.

The organic residues from the dark, organic-rich shales and grey siltstones from Nordaustlandet in palynological slides seem composed of a matrix of granular material, sheet-like unstructured material and *Tasmanites* algae. The granular material dominates in residues from the dark shale: *Tasmanites* cells are moderately small-sized, but bigger cells with strongly degraded walls occur occasionally. The organic residues from the siltstones contain well-preserved remains of large *Tasmanites* cells, and palynomorphs that are generally better preserved than those recovered from the mudstone.

The organic material from both lithologies is relatively insensitive to chemical (oxidative) treatment. From the palynology, it may therefore be suggested that the granular (amorphous and disseminated), and strongly degraded, organic material in the dark shales represents the palynological equivalent to the "matrix kerogen" described in organic petrographic studies.

Rock-Eval pyrolysis results show that the dark shale from Nordaustlandet is a good source rock which contains dominantly type-II kerogen and has reached an early stage of oil generation. The grey siltstone is still immature as a

source rock, and a higher temperature would be needed to initiate oil generation from its well-preserved *Tasmanites* cells, representing kerogen type-I. *Tasmanites* may potentially "improve" the liquid hydrocarbon generation potential of source rocks on the Barents Shelf.

Tasmanitid algae are known to occur in a variety of depositional environments (Guy-Ohlson 1988), and have been described from deposits of Cambrian to recent times. The success of these green algae is probably closely connected to their tolerance of variable salinity and temperature. Their growth through lipid synthesis depends on light intensity, nutrient supply and water temperature. Small algae today appear in the Mediterranean, and, as nonmotile phycmata, float passively with surface waters through the Bay of Biscay northwards. Blooms of *Tasmanites* happen regularly, two or three times a year, in the western British Channel (Parke et al. 1978).

The present Mediterranean region and the life cycle of prasinophycean algae may serve as an environmental model for the palaeo-Barents Shelf and the production of its organic-rich deposits. The scenario for Ladinian–Carnian black shale material on Nordaustlandet is a periodically quiet marine shelf, at times with stratified water masses, and water temperatures similar to the present-day Mediterranean and Bay of Biscay. The shelf was richly supplied with nutrients through run-off from the eroding land areas (Doré 1992; Parrish & Curtis 1982), and currents, possibly from the north-west, concentrated a stock of living plankton, including mature *Tasmanites* phycmata (algal bloom) that shed their living content. Storms disturbed the organic-rich deposits and concentrated the largest phycmata in grey silty deposits. Corresponding occurrences of *Tasmanites* in Siberia indicate that similar depositional conditions occurred all along the northern margin of Pangea.

Conclusions

Very good source rocks for hydrocarbons, with a high content of type-II kerogen, are concentrated in the Middle Triassic deposits of the Botneheia Formation, and in the correlative beds in the Barents Sea. The records of abundant *Tasmanites* confirm that prasinophycean algae are important contributors of organic material in these oil-prone deposits on the Barents Shelf. As a floral element, in marine Triassic deposits, *Tasmanites* appear together with abundant *Micrhystridium*, *Veryhachium* and other plankton in Olenekian, Anisian, Ladinian, Carnian, and Norian deposits of central and eastern Svalbard, the Barents Shelf and further eastwards along the northern Pangea margin.

The Ladinian–Carnian sediment on Nordaustlandet contains abundant *Tasmanites* that must have been

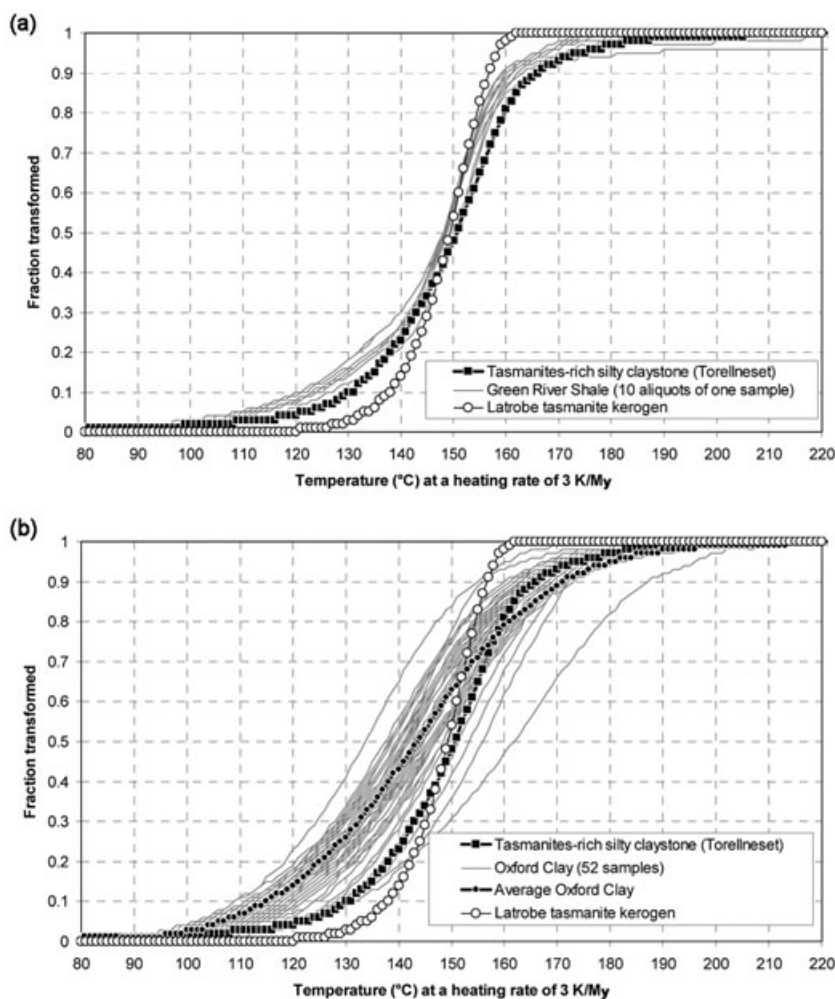


Fig. 8 Bulk pyrolysis (dry, open system, temperature-programmed) transformation curve for mid-Triassic, *Tasmanites*-rich, silty mudstone from Torelleset in Svalbard (sample B3 in Table 1; large squares) compared with data published by Peters et al. (2006) for (a) 10 homogenized type-I kerogen samples from the Green River shale (USA) and (b) 52 type-II kerogens from Oxford Clay (UK). The transformation curve of tasmanite from Latrobe, Tasmania (Revill et al. 1994) is shown for comparison.

deposited from a very large stock of mature *Tasmanites* phycococci. The environment must have had a regular and ample nutrient supply, considering the high production of lipoids and the growth of these cells. During such algal blooms in the upper stratified water masses, oxygen supply to the underlying water column and sea bottom was prevented. Free-swimming larvae or bivalves living on the sea floor, as well as the fauna living within the top sediment layers, therefore suffered from oxygen deficiency at these times.

The death assemblages of bivalve microcoquina and *Tasmanites* were preserved under anoxic sea bottom conditions. The uniformly large (500–600 μm in diameter) *Tasmanites*, that had shed their cell content, and the microcoquinas recovered from the siltstones represent storm-agitated, recycled material that settled out of suspension with the silt fraction, and were preserved by being covered by organic-rich fine mud, thereby preventing oxygen supply.

The type-II kerogen represents pollen, spores and abundant microplankton deposited in a marine environment. The oil generation potential of the Botneheia Formation may have been improved by the input of algal type-I kerogen, in the form of *Tasmanites*. However, because of the additional type-I kerogen, increased temperatures are required for liquid hydrocarbon generation. Sediments of Middle–Late Triassic age may also have a fair input of type-II kerogen in areas that are not too close to the palaeocoastlines. The preservation and enrichment of *Tasmanites* are believed to have been controlled by the basinal configuration, and by the post-mortem depositional regimes.

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