

Svalbard Composite Tectono-Sedimentary Element, Barents Sea



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Abstract: The Svalbard Composite Tectono-Sedimentary Element (SCTSE) is located on the northwestern corner of the Barents Shelf and comprises a Carboniferous–Pleistocene sedimentary succession. Due to Cenozoic uplift, the succession is subaerially exposed in the Svalbard archipelago. The oldest parts of the succession consist of Carboniferous–Permian mixed siliciclastic, carbonate and evaporite, and spiculitic sediments that developed during multiple phases of extension. The majority of the Mesozoic succession is composed of siliciclastic deposits formed in sag basins and continental platforms. Episodes of Late Jurassic and Early Cretaceous contraction are evident in the eastern part of the archipelago and in nearby offshore areas. Differential uplift related to the opening of the Amerasian Basin and the Cretaceous emplacement of the High Arctic Large Igneous Province created a major hiatus spanning from the Late Cretaceous and early Danian throughout the Svalbard CTSE. The West Spitsbergen Fold and Thrust Belt and the associated foreland basin in central Spitsbergen (Central Tertiary Basin) formed as a response to the Eurekan Orogeny and the progressive northward opening of the North Atlantic during the Paleogene. This event was followed by the formation of yet another major hiatus spanning the Oligocene–Pliocene. Multiple reservoir and source-rock units exposed in Svalbard provide analogues to the prolific offshore acreages in the SW Barents Sea, and are important for the de-risking of plays and prospects. However, the archipelago itself is regarded as a high-risk acreage for petroleum exploration. This is due to Paleogene contraction and late Neogene uplift of the western and central parts in particular. There is an absence of mature source rocks in the east, and the entire region is subjected to strict environmental protection.

Supplementary material: Supplementary material 1–5 containing photographs and descriptions of tectono-stratigraphic elements 1–7 are available at <https://doi.org/10.6084/m9.figshare.c.6404502>.

Located at the northwestern corner of the Eurasian continental plate (Enclosure D), the Norwegian High-Arctic Svalbard archipelago represents an uplifted and exposed part of the western Barents Shelf (Fig. 1). Because of its position, the archipelago offers insights into the structural evolution of the western Barents Shelf margin and adjacent Arctic regions, such as NE Greenland. In particular, the rocks in Svalbard record the events related to the opening of the NE Atlantic and Arctic oceans. The Carboniferous–Paleogene sedimentary succession provides analogues to the age-equivalent strata in the basins offshore. Geological and geophysical data from the archipelago are frequently used in regional resource estimates and to de-risk prospects on the Barents Shelf. Despite the many similarities, especially in the Upper Paleozoic–Mesozoic platform successions, the structural evolution of Svalbard differs from the oil- and gas-bearing offshore basins by the absence of extensional tectonics related to the development of the Late Jurassic North Atlantic rift system and the presence of thrust tectonics related to the Eurekan Orogeny.

Industrial commercial petroleum exploration in Norway started in Svalbard in the early 1960s, before the first North Sea concession round in 1965. No commercial discoveries were made on the archipelago (Senger *et al.* 2019) – which is arguably positive in hindsight, given the unique and fragile ecosystem of Svalbard. Nonetheless, Svalbard's outcrops have been instrumental in training petroleum geologists from Norway and elsewhere to decipher petroleum system

elements better and in improving understanding of other parts of the Norwegian Continental Shelf.

In the Svalbard Composite Tectono-Sedimentary Element (SCTSE), as in the southwestern Barents Sea (SWBS), deep burial, probably at its maximum during the late Paleogene, followed by severe uplift during the late Neogene (Nyland *et al.* 1992; Dimakis *et al.* 1998; Lasabuda *et al.* 2018, 2021) in combination with Pleistocene glaciations are probably the biggest risk for commercial oil and gas accumulations. Svalbard itself is an extremely high-risk exploration area for oil and gas.

In contrast to the unsuccessful oil exploration, coal mining has been the most important industrial activity in Svalbard for more than a century. Predominantly Russian and Norwegian companies have been mining Paleogene and Carboniferous coal, with *c.* 78 Mt (million metric tons) of Paleocene and *c.* 9 Mt of Mississippian coal having been produced in the archipelago since the beginning of industrial mining (Jochmann *et al.* 2015). Today, there is one active coal mine in Barentsburg and one in Longyearbyen, where Paleocene, high-volatile, bituminous coal is extracted.

In this chapter, we present a comprehensive and up-to-date overview of the geology and petroleum geology of the SCTSE, herein defined as the Carboniferous–Paleogene sedimentary rock succession and its associated structural elements. As such, the underlying economic basement consisting of Devonian and older sedimentary rocks, as well

From: Drachev, S. S., Brekke, H., Henriksen, E. and Moore, T. (eds) *Sedimentary Successions of the Arctic Region and their Hydrocarbon Prospectivity*. Geological Society, London, Memoirs, 57,

<https://doi.org/10.1144/M57-2021-36>

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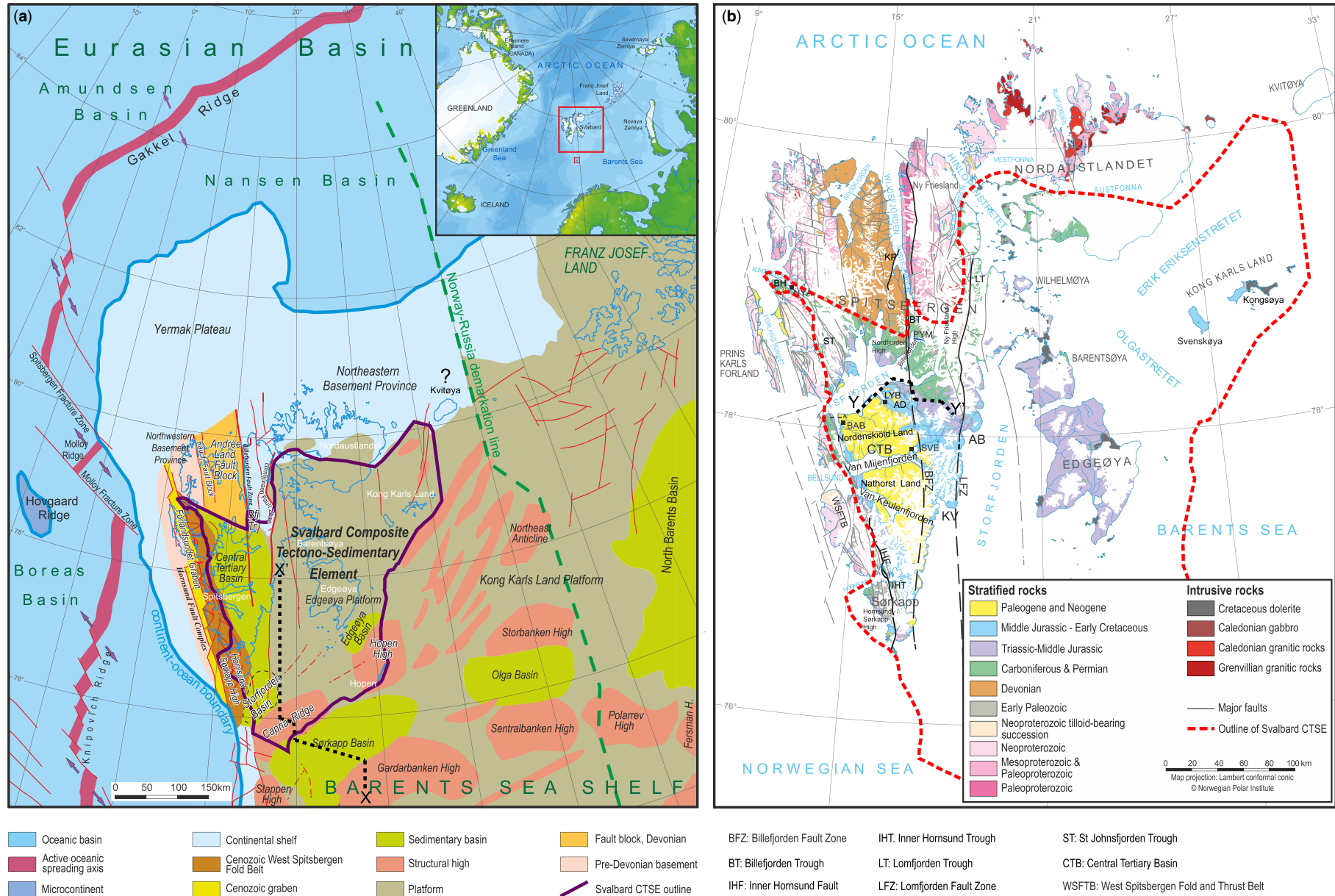


Fig. 1. (a) Structural framework of the Svalbard Composite Tectono-Sedimentary Element. (b) Geological map of Svalbard excluding Bjørnøya. Only the area within the black line in (a) and stippled line in (b) is discussed in this paper. AB, Agardhbukta; BAB, Barentsburg; KV, Kvalvågen; LYB, Longyearbyen; NYÅ, Ny Ålesund; PYM, Pyramiden; SVE, Svea. Source: geological maps from [Dallmann \(2015\)](#) and the Norwegian Polar Institute.

Svalbard CTSE

as Precambrian igneous and metamorphic rocks, are not considered. The SCTSE (Fig. 1a, b) is located between approximately 76° and 80° N and 12° and 30° E, and covers an area of c. 121 000 km². The offshore areas adjacent to the SCTSE (Enclosure E) are presented in the North Barents CTSE chapter (Lundschien *et al.* 2023) while the western margin, including the WSFTB, is discussed in the West Barents Sheared Margin CTSE chapter (Faleide *et al.* in review).

Age

The Carboniferous–Lower Cretaceous succession is stratigraphically almost complete, whereas the younger succession is stratigraphically less complete with a major regional hiatus spanning the latest middle Albian–latest Danian (Steel and Worsley 1984; Jochmann *et al.* 2020). Although not substantiated by any biostratigraphic data, a possible Oligocene age has previously been suggested for the youngest part of the Paleogene succession of the Central Tertiary Basin (CTB). In addition, a sliver of middle Oligocene marine mudstone occurs in a fault-bound basin within the West Spitsbergen Fold and Thrust Belt (WSFTB; Schaaf *et al.* 2021).

Geographical location and dimensions

The Svalbard archipelago, which includes all islands between 71°–81° N and 10°–35° E, is bounded in the west and north by Cenozoic passive continental margins facing the NE Atlantic and Arctic oceans, respectively (Fig. 1a; Enclosure A) (Faleide *et al.* 2008; Piepjohn *et al.* 2016). Nearly 60% of the exposed landmasses of the Svalbard archipelago is covered by glaciers (slightly less extensive glacier cover within the SCTSE). The basement provinces and WSFTB in Svalbard are characterized by an alpine topography with rugged peaks ranging up to 1700 m above sea level, whereas the landscape within the SCTSE is dominated by lower and less alpine ‘table-top’ mountains reflecting the presence of layered sedimentary strata. The sparse high-Arctic vegetation in combination with current retreating glaciers enable detailed outcrop investigations. The nearby offshore areas are generally very shallow (typically 50–150 m water depths), whereas most of the larger

fjords tend to be deeper, recording a significant deepening in their outer parts (e.g. outer Isfjorden: >400 m deep).

Principal datasets

The principal datasets used and reviewed in this paper include large amounts of conventional outcrop data (i.e. sedimentological, stratigraphical and structural data) derived from published papers and recent unpublished studies, well data including core and wireline logs, onshore and offshore 2D reflection seismic, and potential field data (magnetic and gravimetric data). The locations of wells and seismic lines are shown in Figure 2.

Wells

This study utilizes available data from 18 petroleum exploration wells drilled in Svalbard from 1961 to 1994 (Table 1) (Nøttvedt *et al.* 1993; Senger *et al.* 2019), research boreholes in Adventdalen (DH1–DH8; Olaussen *et al.* 2019) and Nathorst Land (well BH 10-2008 ‘Sysselmannbreen’: Johansen *et al.* 2011; Johannessen *et al.* 2011), and selected coal exploration boreholes drilled by the Norwegian coal mining company Store Norske Spitsbergen Kullkompani (SNSK).

Seismic data

Figure 2 shows the 2D reflection seismic data coverage, both onshore and offshore. Seismic imaging and resolution, as exemplified in Figure 3, are major problems offshore the western part of the SCTSE due to high velocities (> 4–5 km s⁻¹) in strongly lithified sediments on the seafloor (Eiken 1985, 1994).

Onshore, problems arise from the heterogeneous permafrost (Johansen *et al.* 2003). Seismic profiles are confined to the main fjords, and the onshore seismic data are restricted to the main valleys of Nordenskiöld Land (Bælum and Braathen 2012; Braathen *et al.* 2012) and Nathorst Land (Johansen *et al.* 2011). Seismic data have been presented by Eiken (1994), Bergh *et al.* (1997), Grogan *et al.* (1999, 2000), Johannessen

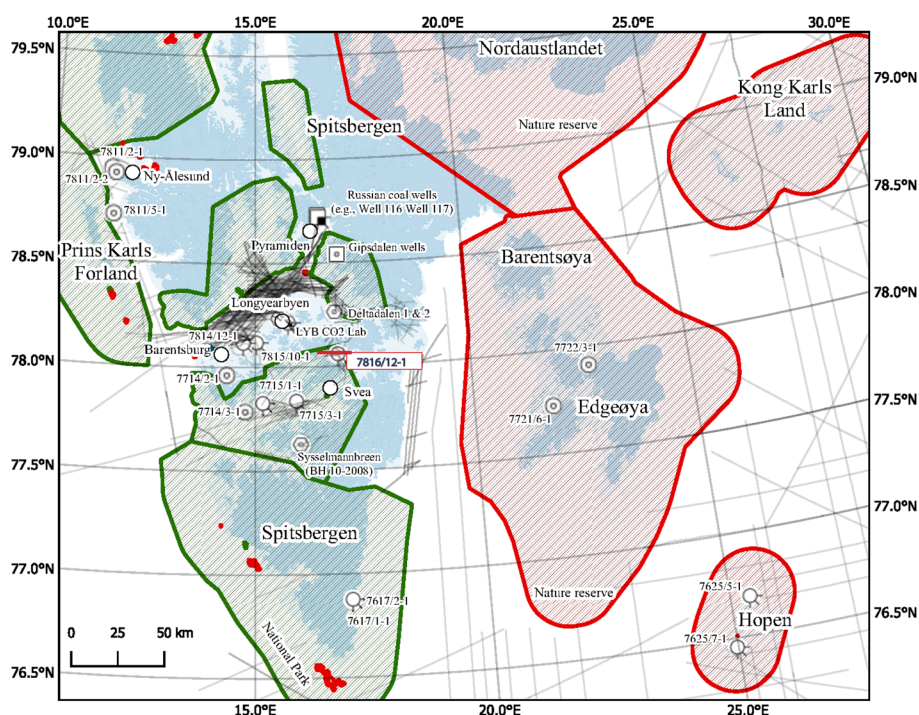


Fig. 2. Principal datasets. 2D conventional seismic lines are shown as grey lines. Hydrocarbon exploration wells are marked with numbers $7nm/n-n$ and follow the annotation recommended by the Norwegian Petroleum Directorate (NPD). Others are coal drilling or R&D wells. The red line at 7816/12-1 is the location of the seismic cross-section in Figure 8. The green hatched areas are national parks, while red hatched areas are national reserves.

Table 1. Exploration boreholes from 1961 to the last exploration, which was well drilled in 1994

No.	NPD well ID	Easting	Longitude	Spudded	Operating company	Elevation KB (m)	Youngest age	Oldest age	Likely reservoir target	Likely reason for drilling and other comments
	Borehole name	Northing	Latitude	Completed		Total depth (m MD)	Youngest formation	Oldest formation	Tectono-stratigraphic element (TSE)	
0	- Kvadehøken I	422970 8766727	11°23'23" 78°57'03"	summer 1961 6/16/1963	NPN	0 479	Early Permian Gipshuken Fm	Pre-Devonian Hecla Hoek	TSE 3	Surface mapping with some oil stains from airport planning. Easily accessible coastal area.
1	7714/2-1 Grønnefjorden I	484198 8654805	14°20'36" 77°57'34"	6/9/1963 8/12/1967	NPN	7.5 971.6	Early Cretaceous Carolinefjellet Fm	Late Triassic De Geerdalen Fm	Wilhelmøya Subgroup TSE 4	Surface mapping. Structurally complex area in WSFB.
2	7715/3-1 Ishøgda I*	522340 8640201	15°58'00" 77°50'22"	8/1/1965 3/15/1966	Amoseas	18 3304	Paleocene Grumantbyen Fm	Early Permian Gipshuken Fm	Numerous potential reservoirs TSE 3, TSE 4	Surface mapping, but drilled on an offset structure as confirmed by later 2D seismic acquisition. First true deep wildcat.
3	7714/3-1 Bellsund I	493959 8634503	14°46'00" 77°47'00"	8/23/1967 8/10/1981	NPN	0 405	Late Jurassic Agardhfjellet Fm	? ?	Wilhelmøya Subgroup? TSE 4	Surface mapping and some gas seepage onshore. Easily accessible coastal area.
4	7625/7-1 Hopen I*	761068 8507624	25°01'45" 76°26'55"	8/11/1971 9/29/1971	Fina	9.1 908	Late Triassic De Geerdalen Fm	Middle Triassic Botneheia Fm	? TSE 4	Surface mapping.
5	7722/3-1	678904	22°41'50"	4/2/1972	CFP	84	Late Permian	Ordovician	?	Surface mapping. Regional geophysical data.
6	Raddedalen 7721/6-1	8660316 659992	77°54'10" 21°50'00"	7/12/1972 6/29/1972	Fina	2823 144.6	Kapp Starostin Fm Middle Triassic	Horbyebeen Fm Pre-Devonian	TSE 1, TSE 3 ?	Surface mapping. Regional geophysical data.
7	Plurdalen 7811/2-1	8638282 422970	77°44'33" 11°23'23"	10/12/1972 9/1/1972	NPN	2351 0	Botneheia Fm Early Permian	? Pre-Devonian	TSE 0, TSE 1, TSE 3 ?	Surface mapping.
8	Kvadehøken II 7625/5-1	8766727 767641	78°57'03" 25°28'00"	6/19/1973 6/20/1973	Fina	479 314.7	Gipshuken Fm Late Triassic-Middle Jurassic	Hecla Hoek Middle Carboniferous	TSE 0, TSE 3 Numerous potential reservoirs	Some limited offset 2D seismic offshore Hopen. Otherwise surface mapping.
9	Hopen II* 7811/2-2	8535807 424853	76°41'15" 11°33'11"	10/20/1973 8/13/1973	NPN	2840 0	Wilhelmøya Subgroup Early Permian	Ebbadalen Fm ?	TSE 2, TSE 3, TSE 4 ?	Surface mapping.
10	Kvadehøken III 7811/5-1	8764140 422845	78°55'32" 11°28'40"	6/16/1974 8/15/1974	NPN	394 5	Gipshuken Fm Oligocene	? Pre-Devonian	TSE 0, TSE 3 ?	Surface mapping. Easy access to drill site
	Sarstangen‡	8741814	78°43'36"	12/1/1974		1113	Sarstangen conglomerate	Hecla Hoek	TSE 6	
11	7815/10-1 Colesbukta‡	500325 8671916	15°02'00" 78°07'00"	11/13/1974 12/1/1975	TA	12 3180	Paleocene Basilika Fm	Early Permian Gipshuken Fm	Numerous potential reservoirs TSE 3, TSE 4	Surface mapping. Easy access to drill site and logistics, at a Russian coal mining settlement.
12	7617/1-1	552582	17°05'30"	9/11/1976	NPN	6.7	Early Cretaceous	Late Triassic-Middle Jurassic	Wilhelmøya Subgroup	Surface mapping.
13	Tromsøbreen I 7715/1-1	8533670 503990	76°52'31" 15°11'15"	9/19/1977 1/10/1985	TA	990 15.13	Carolinefjellet Fm Eocene	Wilhelmøya Subgroup Carboniferous (?)	TSE 4 Numerous potential reservoirs	Surface mapping.
14	Vassdalen II‡ 7617/1-2	8639407 552650	77°49'57" 17°05'38"	7/14/1987 7/20/1987	T-PG	2481 6.7	Frysjaodden Fm Early Cretaceous	Billefjorden Gp (?) Early Permian	TSE 1 (?), TSE 3, TSE 4 Numerous potential reservoirs	Surface mapping.
15	Tromsøbreen II‡ 7715/1-2	8533700 503990	76°52'31" 15°11'15"	8/24/1988 2/28/1988	TA	2337 15.13	Carolinefjellet Fm Eocene	Gipshuken Fm Middle Triassic	TSE 2, TSE 3, TSE 4 Numerous potential reservoirs	Surface mapping.
16	Vassdalen III‡ 7816/12-1	8639407 544775	77°49'57" 16°56'31"	9/1/1989 1/17/1991	NH/SNSK	2352 182.5	Frysjaodden Fm Early Cretaceous	Botneheia Fm Middle Carboniferous	TSE 3, TSE 4 Numerous potential reservoirs	Sparse 2D seismic acquisition prior to drilling. Comprehensive surface mapping.
	Reindalspasset I*	8665611	78°03'28"	4/11/1991		2315	Carolinefjellet Fm	Hultberget Fm	TSE 1, TSE 3, TSE 4	
17	7814/12-1 Kapp Laila I*	493560 8671260	14°53'38" 78°06'52"	2/22/1994 5/8/1994	SNSK/TA/ NH	5 503.5	Paleocene Basilika Fm	Early Cretaceous Carolinefjellet Fm	Helvetiafjellet Formation TSE 4	Surface mapping. Nearby coal exploration.

*wells with reported gas shows

‡wells that tested gas in producible quantities

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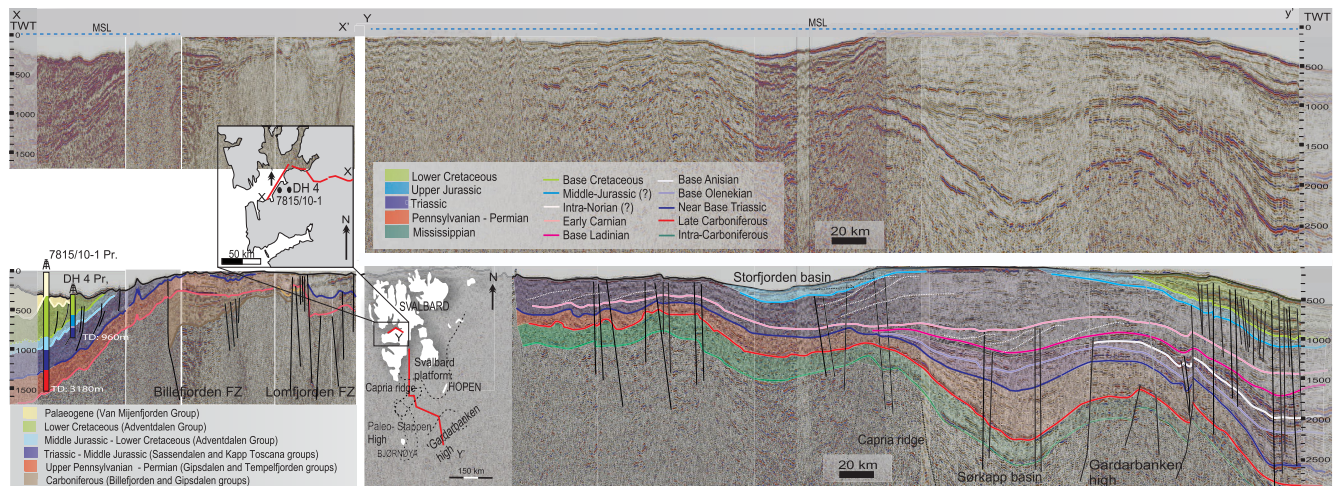


Fig. 3. Uninterpreted and interpreted composite seismic lines crossing central Spitsbergen from west to east, continuing offshore in a southwards direction to the Gardarbanken High south of the SCTSE. The location of line X–X' is shown in Figure 1a and the location of Y–Y' is shown in Figure 1b. MSL, mean sea level; Pr., well projected; TD, total depth; TWT, two-way travel time.

et al. (2011), *Blinova et al.* (2013), *Senger et al.* (2013), *Anell et al.* (2014a, b, c) and *Roy et al.* (2015).

Six of the exploration wells (Reindalspasset, Colesbukta, Kapp Laila, Vassdalen II and III, and Ishøgda) and two research boreholes (Sysselmannbreen DH 2 and DH4) can be tied to 2D seismic data (Fig. 3). Only the prospect in the Reindalspasset well 7816/12-1 was drilled based on sparse 2D acquisition and limited seismic mapping, and tested a conventional play model (*Senger et al.* 2019).

Outcrop and subsurface studies

There has been a long history of geological investigations in Svalbard, with much of the early work focusing particularly on lithological and structural mapping, palaeontology, and various stratigraphic aspects of the sedimentary rock succession. This work has been summarized by a series of geological maps published by the Norwegian Polar Institute (NPI) and in numerous articles and books (e.g. *Steel and Worsley* 1984; *Harland* 1997; *Dallmann et al.* 1999; *Vigran et al.* 2014; *Dallmann* 2015). Digital outcrop models, particularly from drone-based acquisition, are increasingly available and shared via the Svalbox repository (*Senger et al.* 2021). The efforts of previous investigations thus form the framework for this paper.

Gravity and magnetic data were acquired and compiled by the Geological Survey of Norway and are presented in *Nasuti et al.* (2015). The regional aeromagnetic data were acquired with relatively large line spacing (2–8 km) and high sensor elevation (250–1550 m), and are supplemented by ship-based magnetic data in Isfjorden (*Senger et al.* 2013). Gravity data incorporate both relatively dense surface stations, especially along the coastlines, and marine surveys around Svalbard.

Regional magnetotelluric (MT) profiles were acquired to characterize the geothermal potential of Nordenskiöld Land (*Beka et al.* 2016, 2017b) and Brøggerhalvøya (*Beka et al.* 2017a), and provide additional constraints on the regional tectonic structure of the area through subsurface conductivity profiles.

Tectonic setting, boundaries and main tectonic/erosional/depositional phases

The Latest Devonian Cenozoic evolution of the SCTSE is grouped into seven separate tectono-sedimentary elements (TSE 1–TSE 7). The main tectonic events, lithostratigraphic

subdivision of the investigated succession and the hydrocarbon play elements are summarized in Figure 4.

The western boundary of the SCTSE is bounded along the eastern margin of the highly deformed WSFTB, which locally includes overthrust Precambrian–Paleogene successions. The inverted Carboniferous Capria Ridge and southern rim of the Hopen High (*Anell et al.* 2016) mark the southern edge of the SCTSE (Fig. 1a). The Carboniferous and part of the Permian are mainly fault bounded to basement in the north and NE, which defines the northern boundary of the SCTSE. Elsewhere, the northern boundary is defined by the last cropping out Carboniferous–Paleogene strata overlying the economic basement. Initial subsidence during the earliest Mississippian, locally late Fammenian, promoted the development of an interior continental basin within a continental platform (TSE 1). The basin fill is assigned to the Billefjorden Group. The development during this phase is partly disputed, with the discussion evolving around a pre- or synkinematic structural regime. Extensional basins are suggested in the southern and western parts of Spitsbergen (*Cutbill and Challinor* 1965; *Holliday and Cutbill* 1972; *Gjelberg and Steel* 1981; *Braathen et al.* 2011; *Maher and Braathen* 2011; *Smyrak-Sikora et al.* 2021).

The Late Mississippian–Middle Pennsylvanian rifting resulted in the formation of a series of elongated, north–south-orientated fault-bounded basins on Spitsbergen (*McCann and Dallmann* 1996; *Braathen et al.* 2011; *Maher and Braathen* 2011; *Bælum and Braathen* 2012; *Smyrak-Sikora et al.* 2019, 2021). This synrift tectono-sedimentary element (TSE 2) is well documented in the Billefjorden Trough of central Spitsbergen (Fig. 1b).

Waning fault activity and regional subsidence during the Late Pennsylvanian–Early Permian in combination with continued northward continental drift promoted the development of an extensive and long-lived carbonate platform (TSE 3; Fig. 4) (*Stemmerik and Worsley* 2005). This post-rift TSE 3 comprises the upper part of the Gipsdalen Group (Fig. 4).

Renewed extension in the late Early Permian (Artinskian) is linked to the Permian–Triassic development of the North Atlantic rift system along the western margin of the Barents Sea and East Greenland (*Seidler et al.* 2004; *Riis et al.* 2008; *Clark et al.* 2014; *Anell et al.* 2016; *Tsikalas et al.* 2021). A cool-water carbonate platform developed during this synrift phase (TSE 4; Fig. 4). Fault-related uplift of the basin margins controlled the facies and thickness variations of the spiculite, carbonate and siliciclastic facies in the Tempelfjorden Group.

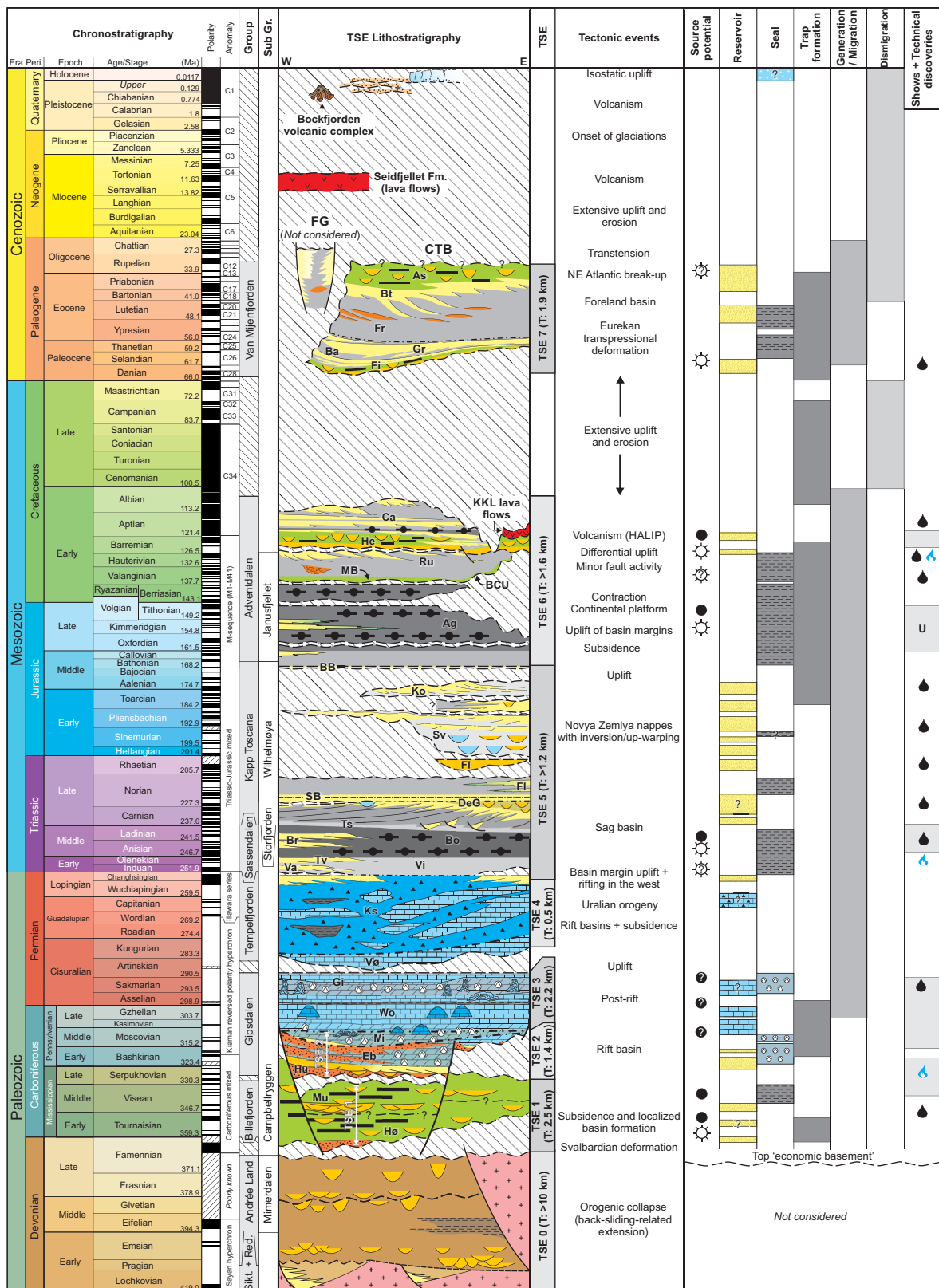


Fig. 4. Composite summary of chronostratigraphy/lithostratigraphy, tectonic events and petroleum systems (i.e. previous petroleum systems) of the tectono-sedimentary sequences (TSE 1–TSE 6) documented in this study. The geological timescale is after Gradstein and Ogg (2020: <https://timescalefoundation.org>). The column is based on the most recent stratigraphic work available, including that of Vigran et al. (2014), Paterson et al. (2016), Smelror et al. (2018), Koevoets et al. (2018), Jochmann et al. (2020) and Śliwińska et al. (2020). BCU, Base Cretaceous Unconformity. Abbreviations of lithostratigraphic units and structural elements (from top down): Ag, Agardhfjellet Fm; As, Aspelintoppen Fm; Ba, Battfjellet Fm; BB, Brentskardhaugen Bed; Bo, Botneheia Fm; Br, Bravaisberget Fm; Bt, Battfjellet Fm; Ca, Carolinefjellet Fm; CTB, Central Tertiary Basin; DeG, De Geerdalen Fm; Eb, Ebbadalen Fm; FG, Forlandsundet Graben; Fi, Firkanten Fm; Fl, Flatsalen Fm; Fr, Frysjaodden Fm; Gi, Gipshuken Fm; Gr, Grumantbyen Fm; He, Helvetiafjellet Fm; Hø, Hørbybreen Fm; Hu, Hultberget; KKL lava flows, Kong Karls Land lava flows; Ko, Kongsøya Fm; Ks, Kapp Starostin Fm; MB, Myklegardfjellet Bed; Mi, Minkenfjellet Fm; Mu, Mumien Fm; Ru, Rurikfjellet Fm; SB, Slottet Bed; Sv, Svenskøya Fm; Ts, Tschermakfjellet Fm; Tv, Tvvillingodden Fm; Va, Vardebukta Fm; Vi, Vikinghøgda Fm; Vø, Vøringen Member; Wo, Wordiekammen Fm.

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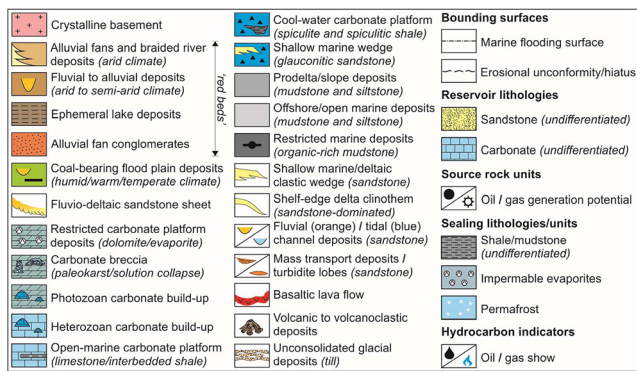


Fig. 4. Continued.

Early Triassic–Middle Jurassic regional subsidence resulted in the development of a sag basin dominated by siliciclastic deposition (TSE 5; Fig. 4). The Middle Triassic–Upper Triassic NW-prograding delta sourced from the denudation from the Uralide mountains and Fennoscandian Shield reach Spitsbergen in the Carnian (Anell *et al.* 2014a; Klausen *et al.* 2019). In addition, a less prominent western source contributed to deposition in the western and southern parts of the SCTSE (Mørk *et al.* 1982; Krajewski and Weitschat 2015; Czarniecka *et al.* 2020). A condensed Norian–Pliensbachian succession, <10 m thick and with numerous internal hiatuses in the west, thickens eastwards to a >200 m-thick, stratigraphically almost complete, succession (Fig. 4). The subsidence of the succession in the east is suggested to be linked to the Novaya Zemlya Orogen. (Olaussen *et al.* 2018; Müller *et al.* 2019).

Late Middle Jurassic–Early Cretaceous regional subsidence with uplift in the north and NW formed a continental, siliciclastic platform (TSE 6; Fig. 4). Early Cretaceous circum-Arctic magmatism resulted in the emplacement of the High Arctic Large Igneous province (HALIP), which eventually became a prominent sediment source from the Barremian onwards (Maher 2001; Grantz *et al.* 2011; Polteau *et al.* 2016). Local extensional faulting occurred on Spitsbergen (Onderdonk and Midtkandal 2010) and some minor contraction took place in the east, at Kong Karls Land and Kong Karls Land Platform (Grogan *et al.* 1999, 2000; Olaussen *et al.* 2018).

The latest middle Albian–latest Danian hiatus records exhumation of the entire SCTSE with a significant component of northerly uplift, probably induced by magmatism and the opening of the Amerasian Basin north of Svalbard (Maher 2001). Plate tectonic reorganization initiated by the opening of the North Atlantic Ocean may also have contributed to the uplift and the development of this major hiatus (e.g. Faleide *et al.* 2008). The occurrence of Late Cretaceous terrestrial and marine microfloras in Paleocene strata in southern Spitsbergen indicates erosion and reworking of previous deposited Upper Cretaceous strata (Smelror and Larssen 2016).

North-directed opening of the North Atlantic Ocean culminated with the formation of a transform fault along the De Geer Zone, linking the Atlantic and Arctic basins. This zone had a major impact on the Paleogene development of the SCTSE. During the Paleocene, dextral movement between the Eurasian and Greenland plates caused transpression-induced crustal shortening (e.g. Bergh *et al.* 1997; Leever *et al.* 2011), with the formation of the WSFTB and its flanking foreland basin, the CTB (Steel *et al.* 1981; Helland-Hansen 1990; Braathen *et al.* 1999; Helland-Hansen and Grundvåg 2020). The foreland basin fill is assigned to TSE 7 (Fig. 4) and further suggests that the main phase of contraction-driven uplift in the west, along the De Geer Zone, appeared in the Eocene (TSE 7; Fig. 4). Subsequent graben formation within the De Geer Zone and WSFTB during the late Eocene–

Oligocene indicates a shift from transpression to transtension driven by changes in plate motion (Maher *et al.* 1997, 2020; Braathen *et al.* 1999).

Finally, the current Neogene passive-margin development was accompanied by recurrent periods of uplift, erosion and glaciation from 3.6 Ma (Knies *et al.* 2009). Crustal thinning and the onset of oceanic spreading close to western Spitsbergen probably governed the development of a Neogene hiatus across the Svalbard archipelago and the surrounding shelf areas (Green and Duddy 2010).

The central and western parts of the archipelago and the northwestern part of the Barents shelf margin in particular have been subjected to significant uplift over the last few million years (Dimakis *et al.* 1998; Henriksen *et al.* 2011a; Lasabuda *et al.* 2018), and the presence of thick pre-glacial (probably Miocene and Pliocene) and glacial (late Pliocene and Pleistocene) clastic wedges offshore west Spitsbergen (Hjelstuen *et al.* 1996) suggests a net denudation of *c.* 3 km (Riis and Fjeldskaar 1992). This is in overall agreement with uplift estimates in the range 2.5–3.5 km based on organic geochemical studies (Thronsdon 1982; Marshall *et al.* 2015; Olausen *et al.* 2019). However, the westernmost margin of the SCTSE might have been subjected to a higher magnitude of uplift or a higher temperature gradient. Remnants of Pleistocene glacial deposits occur locally onshore Spitsbergen, indicating multiple glaciations (Ingólfsson and Landvik 2013). Uplift of 9 mm a⁻¹ is ongoing at present in central western Spitsbergen. However, only 1 mm a⁻¹ of this is attributed to isostatic rebound due to deglaciation following the Late Weichselian glaciation (Kierulf *et al.* 2022). TSEs 1–7 are summarized below (see Supplementary material 1–7 for outcrop examples):

- (1) Uppermost Devonian to Lower Mississippian TSE 1 deposited in an interior continental sag basin possibly related to initial rift stage in SW;
- (2) Serpukhovian to Moscovian synrift TSE 2;
- (3) Upper Pennsylvanian to Lower Permian – postrift sag/platform TSE 3;
- (4) Lower Permian (Artinskian) to the base Triassic synrift TSE 4;
- (5) Base Triassic to lower Middle Jurassic – sag basin TSE 5;
- (6) Upper Middle Jurassic to Lower Cretaceous – continental platform TSE 6;
- (7) Paleogene – foreland basin TSE 7.

Underlying and overlying rock assemblages

Age of underlying basement (consolidated crust) or youngest sedimentary unit

The oldest crystalline basement rocks in Svalbard are dated to 2709 ± 28 Ma (U–Pb zircon ion microprobe; Hellman *et al.* 2001). The youngest rocks below the SCTSE are the metasediments of Middle Fammenian age. Tournaisian–Visean strata exhibit a metasedimentary character in the WSFTB.

Some exploration wells were drilled into metamorphic rocks of Caledonian age (Senger *et al.* 2019) and on Edgeøya an exploration well drilled into carbonate beds of disputed age, possibly being of either Late Devonian or Silurian–Ordovician age at a total drilling depth (TD) of 2283 m (cf. Harland and Kelly 1997). Based on the relatively poor quality of reflection seismic imaging of deeper strata, we suggest that the economic basement in the nearby offshore areas is most likely to be similar to that proven in the onshore areas (Faleide *et al.* 2017).

Age of oldest overlying sedimentary units

The oldest overlying sediments are late Pliocene glacial deposits.

Subdivision and internal structure

One of the main structural characteristics of the SCTSE is the north–south-trending Pennsylvanian rift basins situated along prominent fault zones. In addition, Mesozoic sag basins and platforms, together with the CTB, define the main internal structures of the SCTSE (Fig. 1).

Carboniferous north–south-trending rift basins

The best-exposed example of a north–south rift basin is the Billefjorden Trough between Billefjorden and Austfjorden (Fig. 1b). It is a c. 25 km-wide, westward-dipping and southward-plunging half-graben with main the extensional phases occurring during the Serpukhovian–Moscovian (Maher and Braathen 2011; Smyrak-Sikora *et al.* 2019, 2021). The preserved basin fill forms a westward-thickening wedge, up to 2 km thick on the hanging wall of the north–south-striking, eastward-dipping Billefjorden Fault Zone. Reactivation of normal faulting occurred in the Permian and possibly also during the Early Triassic. The southward continuation of the north–south-trending Carboniferous rift basins is documented by exploration well 7816/12-1 (Fig. 2).

Along the northern part of the complex Lomfjorden Fault Zone, a westward-dipping wedge-shaped Lower Carboniferous basin fill occurs in the Lomfjorden Trough (Fig. 1b) (Gjelberg and Steel 1981; Harland 1997; Blomeier *et al.* 2009). The Lomfjorden Trough is bounded to the west by the north–south-striking basement-dominated high: the Ny Friesland High (Figs 1b, 5 & 6). We speculate that the Ny Friesland High is a Carboniferous horst structure and that the

Lomfjorden Trough represents the remnants of a larger Carboniferous graben (Fig. 6).

Permian reactivation

Reactivation of the north–south-trending faults was important for later structuring in the SCTSE. Renewed rifting occurred in the late Early Permian. This is particularly evident in southern Spitsbergen, where Upper Permian strata are thin and pinch out across the Sørkapp–Hornsund High. In addition, Artinskian–uppermost Permian deposits appear to be downfaulted (by c. 400 m) on the southwestern tip of Sørkapp (Dallmann 2015), thus recording Late Permian fault activity. Thickness variations of the Upper Permian strata demonstrating local fault activity are also observed on the Nordfjorden High (Fig. 6) and Sørkapp–Hornsund High (Hellem 1980; Knag 1980; Blomeier *et al.* 2011; Bond *et al.* 2017) and probably lasted until the early Middle Triassic (Krajewski and Weitschat 2015; Czarniecka *et al.* 2020).

Mesozoic basins and platforms

The Svalbard Platform and the northern part of the Kong Karls Land Platform are the two main internal Mesozoic structures in the SCTSE. Following cessation of Late Paleozoic tectonic activity of the Edgeøya Basin, the Hopen High merged with the Edgeøya Platform to form the Mesozoic Svalbard Platform (Anell *et al.* 2016). Due to poor seismic coverage, its eastern boundary towards the Kong Karls Land Platform is difficult to define. Large, NE-striking Mesozoic synforms and anti-forms with Late Mesozoic and Tertiary reverse faults and

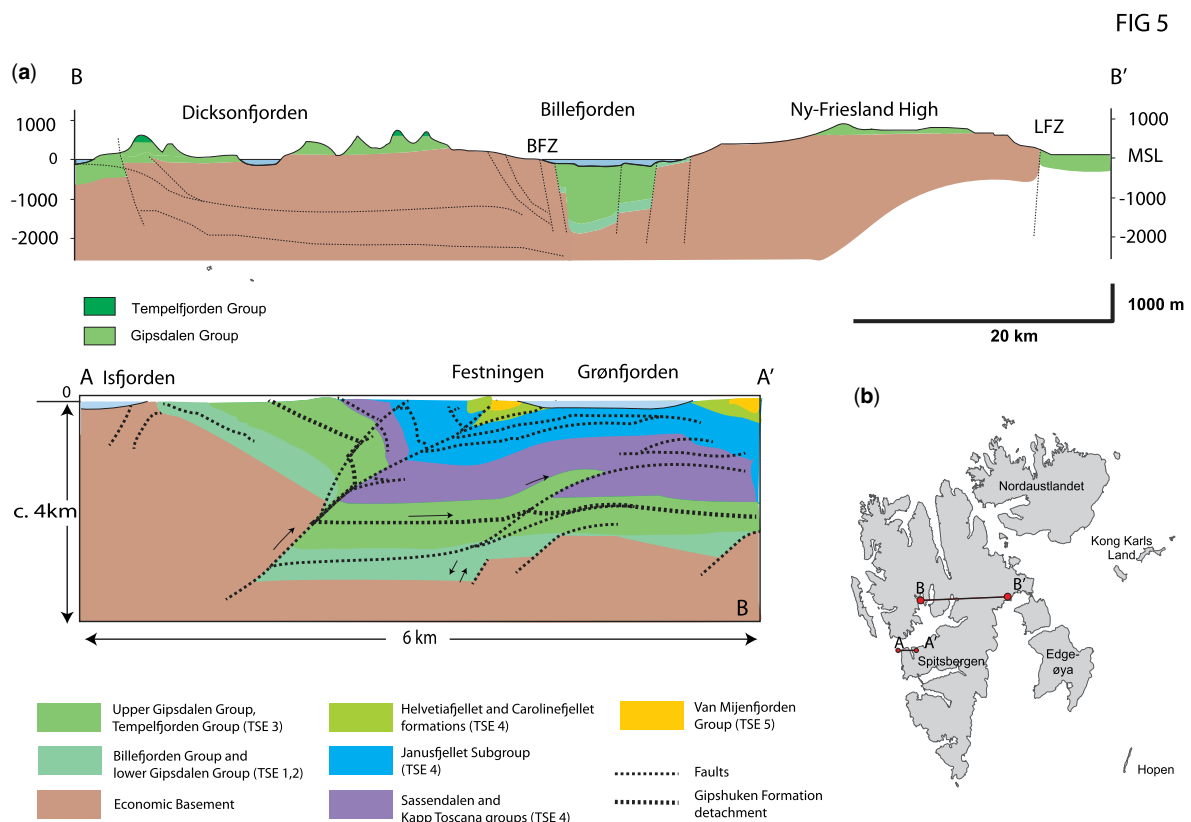


Fig. 5. Cross-sections from Spitsbergen. (a) Cross-section from central to eastern Spitsbergen. Lomfjorden Fault Zone from Haremo and Andresen (1992). The locations of the cross-sections are seen in (b). (b) Cross-section from the West Spitsbergen Fold and Thrust Belt. The estimated depth of the cross-section is based on poor-resolution offshore seismic data (Bergh *et al.* 1997) and a crude velocity model. Source: (a) modified from Dallmann (2015) and Smyrak-Sikora *et al.* (2019); (b) simplified and modified after Braathen *et al.* (1995).

Svalbard CTSE

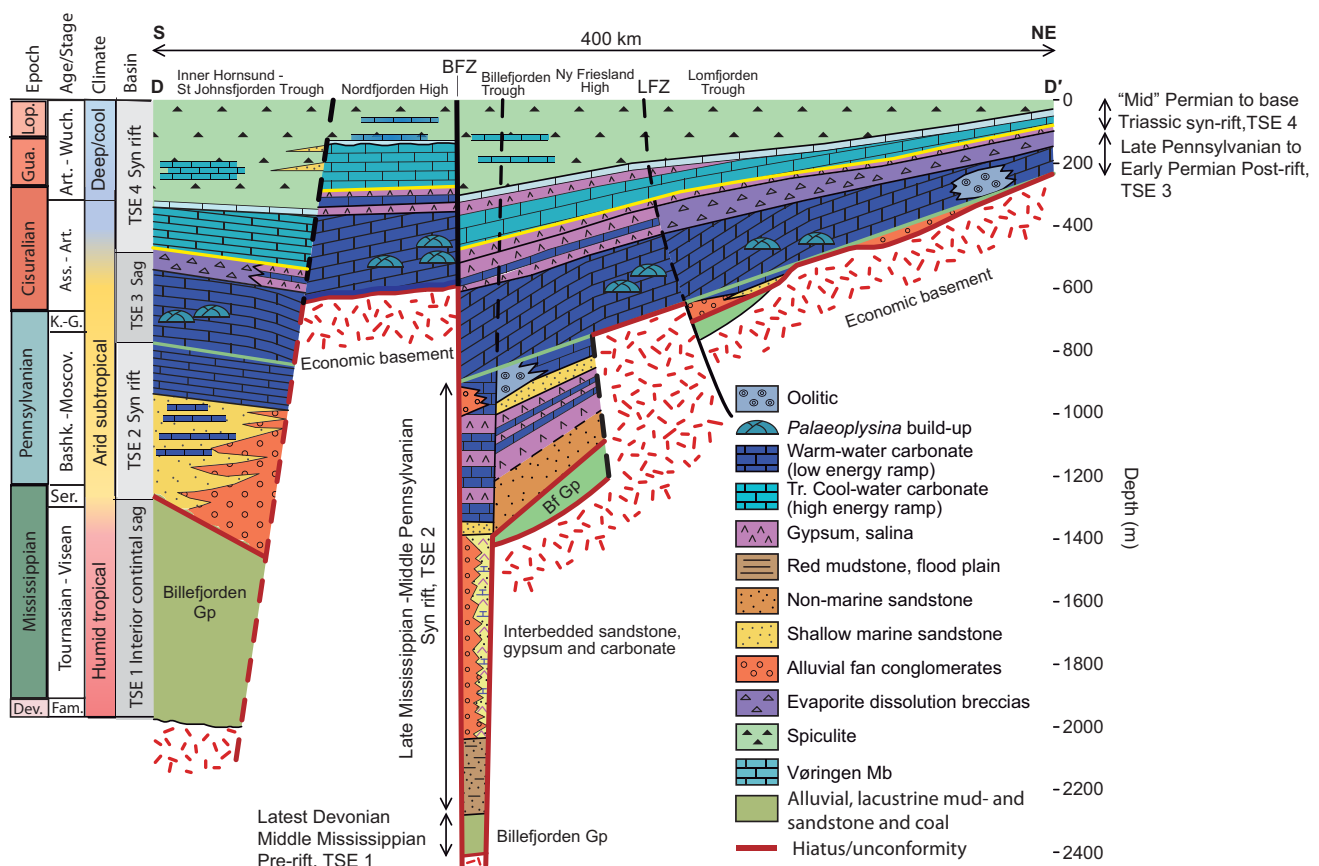


Fig. 6. Stratigraphic structural cross-section of the Carboniferous and Permian from the NE to the southern part of the archipelago. Section from Nordaustlandet, crossing towards the Billefjorden Fault Zone and the Nordfjord High in the SW, and finally southwards to Hornsund (Fig. 1b). Flattened at near top Permian. BFZ, Billefjorden Fault Zone; LFZ, Lomfjorden Fault Zone; Tr. Cool water carbonate, transition to cool-water carbonates. Ny Frisland High as a Carboniferous horst is somewhat speculative.

Lower Cretaceous intrusive or extrusive volcanic rocks characterize the Kong Karls Land Platform (Grogan *et al.* 1999), and gently folded strata with lower Cretaceous volcanic rocks are seen onshore Kong Karls Land (Grogan *et al.* 2000). Two periods of Mesozoic contraction are suggested on Kong Karls Land: one event in the Late Jurassic, probably Kimmeridgian or early Volgian, followed by rejuvenation in the Barremian–Aptian (Olaussen *et al.* 2018). Small-scale rotated fault blocks in the Barremian strata at Kvalvågen suggest instability caused by short-lived tectonic activity along the Lomfjorden Fault Zone.

Reverse faults cutting Permian and the Mesozoic strata are well documented in the Billefjorden Fault Zone at the outer tip of Billefjorden and south of Isfjorden. Haremo and Andresen (1992) showed that the Lomfjorden Fault Zone, west of Agardhbukta, was reactivated by Eocene reverse faulting.

Paleogene basin

The CTB forms an elongated NNW–SSE-orientated syncline that covers an area of *c.* 5000 km² in southern and central Spitsbergen. Its margins were initially bounded by a series of north–south-orientated faults. Uplifted terranes to the north and east were the main source areas for the Paleocene basin fill (e.g. Steel *et al.* 1981, 1985; Bruhn and Steel 2003; Petersen *et al.* 2016). Structural outliers containing correlative Paleocene strata at Brøggerhalvøya (and elsewhere) may indicate that the Paleocene basin was covering a much larger area than presently preserved (Jochmann *et al.* 2020). During the contraction in Eocene, the WSFTB continued to rise, and flexural loading along the western basin margin thus assisted in maintaining the

asymmetrical basin shape, being deepest in the west and shallowing significantly eastwards (Helland-Hansen and Grundvåg 2020). The Paleogene deformed Storfjorden Basin is fault bounded by the Sørkapp–Hornsund High and the anticlinal structure above the Capri Ridge (Anell *et al.* 2016).

The CTB probably developed into a wedge-top basin during the final stages of crustal deformation. The extent of the Eocene basin to the south and east is unknown but it is most likely to have continued far beyond its present-day extent.

After the main transpressional phase in the Eocene, trans-tensional movements along the Hornsund Fault Zone resulted in the formation of a series of basins along western Spitsbergen, including the Forlandsundet Graben.

Sedimentary fill

Total thickness

The thickness of the Carboniferous–Permian successions (TSE 1–TSE 4; Fig. 4) varies from 380 to 1800 m, whereas the Mesozoic successions (TSE 5–TSE 6; Fig. 4) vary from 1480 to 2370 m, thus adding up to 1860 and 4170 m, respectively. The Paleogene succession (TSE 7; Fig. 4) is only preserved in western and central Spitsbergen (Fig. 1a, b) where it varies from 0 to 1700 m. As such, the total thickness of the SCTSE may reach 5870 m. However, this number is somewhat uncertain due to Paleogene shortening of pre-Paleogene strata, particularly in western Spitsbergen (Braathen *et al.* 1999).

None of the nearby seismic lines that were available for this study has been depth converted due to uncertain interval

velocities, which may cause large uncertainties during attempts to estimate thicknesses.

Lithostratigraphy and depositional systems

TSE 1: Tournaisian–Visean Billefjorden Group. The continental sediments of the Billefjorden Group mark the onset of the Mississippian, locally possibly late Fammenian, deposition in the SCTSE. The basal surface is a first-order sequence boundary (cf. Embry 2009), recording large-scale tectonic reorganization (i.e. from the Svalbardian deformation to an interior continental basin). In central Spitsbergen, the basal unconformity is overlain by a c. 100 m-thick coarse-grained unit of fluvial and lacustrine deposits assigned to the lower part of the Hørbybreen Formation (Fig. 4). In western Spitsbergen, deposition started later with the accumulation of fine-grained floodplain deposits assigned to the Tournaisian Orustdalen Formation. Lopes *et al.* (2018) suggested a late Tournaisian–late Visean hiatus in the Hørbybreen Formation. This coincides with a shift in depositional environments from a coarse-grained sand- and gravel-dominated braidplain to a fine-grained, vegetated floodplain dissected by meandering rivers (e.g. Steel and Gjelberg 1981). In the Billefjorden Trough, coarse-grained braided stream deposits are locally overlain by heterolithic and coal-bearing floodplain fines. This formation thickens northwards along the Billefjorden Fault Zone and pinches out towards the underlying basement in the east. The gradual transition from deposits consistent with wetlands into floodplain red beds with calcrete in the Serpukhovian–Bashkirian Hultberget Formation records a change from humid to semi-arid or arid tropical climate. A more detailed description of TSE 1 is available in [Supplementary material 1](#).

TSE 2: Serpukhovian–Moscovian lower Gipsdalen Group. Deposition of the lower Gipsdalen Group took place in a series of narrow, north–south-elongated rift basins under overall arid to semi-arid climatic conditions. In the Billefjorden Trough, deposition occurred in three distinctive phases. The basal, fluvial-dominated Hultberget Formation and the paralic Ebbaelva Member of the Ebbadalen Formation were deposited during early rifting in an overall symmetrical basin (Johannesen and Steel 1992; Smyrak-Sikora *et al.* 2019). During the main extensional phase and half-graben development, wedge-shaped alluvial fans of the Ebbadalen Formation prograded basinwards from the footwall in the west, interfingering with mixed carbonates, siliciclastics and evaporites in more distal locations to the east. During the late rift and early post-rift stages, shallow-marine siliciclastics and carbonates of the Moscovian Minkinfjellet Formation were deposited along the eastern and western basin margins, whereas interbedded gypsum and carbonate accumulated in the central parts of the basin (Fig. 4) (Smyrak-Sikora *et al.* 2021). Cyclicality and facies changes were due to a combination of tectonically induced subsidence and eustatic sea-level changes governed by the global icehouse conditions at these times (Ahlborn and Stemmerik 2015; Smyrak-Sikora *et al.* 2019, 2021). A more detailed description of TSE 2 is available in [Supplementary material 1](#).

TSE 3: upper Moscovian–Lower Permian upper Gipsdalen Group. The upper Pennsylvanian and Lower Permian successions represent a distinctive element in the evolution of the SCTSE with the development of an extensive and long-lived carbonate platform, reflecting a combination of regional subsidence, waning extensional tectonics and eustatic sea level (Stemmerik and Worsley 2005).

Strata included in the Moscovian–lower Sakmarian part of the Gipsdalen Group are assigned to the Wordiekammen Formation, which formed a shallow-marine carbonate platform across the SCTSE. Condensed and amalgamated shallow-marine facies successions dominate across the underlying structural highs such as the well-studied eastern Nordfjorden High (Fig. 6). Thicker, non-amalgamated successions dominate in areas overlying the previous rift-basin centre (Ahlborn and Stemmerik 2015; Sorento *et al.* 2020). Deposition at this time was also strongly influenced by frequent, high-amplitude glacio-eustatically driven relative sea-level fluctuations governed by waxing and waning of ice sheets in the southern hemisphere. A more detailed description of TSE 3 is available in [Supplementary material 2](#).

TSE 4: upper Lower–Upper Permian Tempelfjorden Group. Deposits of the Gipshuken Formation reflect a transition from gypsum deposition in a shallow extensive salina system to deeper, cooler-water carbonate shelf deposition (Sorento *et al.* 2020). The structural control becomes evident in the Artinskian by the uplift of prominent highs such as Nordfjorden High and the Sørkapp–Hornsund High (Hellem 1980; Knag 1980; Matysik *et al.* 2017). The basal Vøringen Member forms a distinctive brachiopod packstone-dominated transgressive sheet-like unit (e.g. Uchman *et al.* 2016). Thickness and facies variations of the Tempelfjorden Group are linked to the Late Permian rift event along the western Barents shelf margin. On the SCTSE, an extensive, cool-water carbonate platform succession developed, assigned to the Tempelfjorden Group (Fig. 4). Spiculites and shale dominates the deeper part of the basin, whereas cool-water carbonates and glauconitic sandstones of shallow-marine (i.e. inner-shelf) origin occur along the basin margins and in the proximity to structural highs (e.g. Blomeier *et al.* 2011, 2013; Bond *et al.* 2017; Uchman *et al.* 2016). Sandstone wedges in the southern part of Spitsbergen are banked onto the Sørkapp–Hornsund High (Knag 1980) and are consistent with an active synrift basin fill. Regional subsidence in combination with a eustatic sea-level rise resulted in deepening of the SCTSE. In addition, continued northward continental drift promoted climatic cooling in concert with globally high-silica production in the oceans. A more detailed description of TSE4 is available in [Supplementary material 2](#).

TSE 5: Triassic–Middle Jurassic Sassendalen and Kapp Toscana groups. The base of the Mesozoic in a shale interval near the base of the Sassendalen Group (Zuchuat *et al.* 2020) marks a regional shift from carbonate and silica/spiculite deposition to siliciclastic deposition across the SCTSE. The Early–Middle Triassic Vardebukta, Tvillingodden and Bravaisberget formations that crop out in western Spitsbergen include coarser-grained, shallow-marine and deltaic wedges that built into the basin from the west (Fig. 4) (Mørk *et al.* 1982; Czarniecka *et al.* 2020). These deposits transition eastwards into offshore mudstones of the Lower Triassic Vikinghøgda Formation and the overlying Botneheia Formation (Fig. 4) (Mørk *et al.* 1999; Vigran *et al.* 2014; Wesenlund *et al.* 2022).

During deposition of the Kapp Toscana Group, the sediment supplied to the SCTSE was mainly sourced from the ESE, recording the distal part of a northwestward-prograding deltaic clinoform system approaching from the Uralian mountains and the northeastern part of the Baltic Shield (Riis *et al.* 2008; Smelror *et al.* 2009; Glørstad-Clark *et al.* 2011; Høy and Lundschieen 2011; Klausen *et al.* 2014, 2017, 2019; Gilmullina *et al.* 2021). The northward progradation of this system was initiated during the latest Permian along the Fennoscandian coastline but did not reach the SCTSE before the Ladinian

(Riis *et al.* 2008; Lundschieen *et al.* 2014; Lord *et al.* 2017). Local highs throughout the eastern part of the SCTSE existed with the Induan part of the succession missing in many places (Mørk *et al.* 1999; Vigran *et al.* 2014; Lord *et al.* 2017). The prodeltaic part of this delta system is represented by the Tschermakfjellet Formation (Ladinian–early Carnian), whereas the overlying De Geerdalen Formation (Carnian–early Norian) represents distal delta front to delta/coastal deposits (Fig. 4) (Klausen and Mørk 2014; Lord *et al.* 2014, 2017; Rød *et al.* 2014; Anell *et al.* 2020). Growth faults and delta collapse are recorded on the west coast of Edgøya (Edwards 1976; Smyrak-Sikora *et al.* 2020). Facies become generally more sandstone rich and increasingly more proximal in the eastern part of the SCTSE (e.g. Hopen, Edgeøya, Wilhelmøya and Barentsøya) than in Spitsbergen (Mørk *et al.* 1982; Lord *et al.* 2017). In the upper part of the formation in Spitsbergen and on Wilhelmøya, the Isfjorden Member consists of heterolithic, intercalated beds of shale, siltstone and sandstone. Red beds with immature to decimetre-thick mature calcrete soil profiles (i.e. hard pans) interbedded with 1–2 m-thick mouth-bar and meandering channel deposits are present, as are calcareous and non-calcareous soil profiles giving the unit a distinctive red and green coloration (Lord *et al.* 2022). These facies indicate that the Isfjorden Member represents a delta-top environment. These more condensed successions and prevalent localized subaerial exposure surfaces at the top of the De Geerdalen Formation are consistent with a proposed reduction in subsidence at the transition to the Norian and Early Jurassic (cf. Ryseth 2014). On Hopen to the SE in the SCTSE, the Hopen Member represents a shallow-marine interval that can be traced east of Svalbard (Lundschieen *et al.* 2014). This is likely to indicate early onset of basin sag and the development of a seaway in this area prior to the Norian flooding at the base of the Wilhelmøya Subgroup. It is presently unclear whether the Hopen and Isfjorden members are time-equivalent units as extensive erosion at the base of the Wilhelmøya Subgroup has recently been reported and the unit may simply be absent on Spitsbergen (Hounslow *et al.* 2022; Klausen *et al.* 2022).

The basal boundary of the lower Norian–lower Bathonian Wilhelmøya Subgroup represents a regional unconformity surface overlain by the conglomeratic Slottet Bed that was deposited during a pan-Arctic Norian flooding event (cf. Embry 1997). In the SCTSE, the basal boundary of the Wilhelmøya Subgroup also marks a change from immature sandstones to more quartz-rich sandstones (Mørk 2013; Lord *et al.* 2019), possibly recording a regional change in the provenance area and the reworking of older sedimentary rocks in concert with a change from semi-arid to more humid climatic conditions.

The Wilhelmøya Subgroup is subdivided into three formations, where the lower mudstone-dominated Flatsalen Formation represents widespread prograding offshore to delta-front deposits. A major subaerial sequence boundary occurs near the base of the Rhaetian, informally referred to as ‘the Rhaetian unconformity’ (cf. Embry 2009; Lord *et al.* 2019). While the Rhaetian–Pliensbachian paralic Svenskøya Formation comprises an almost 200 m-thick succession in Kong Karls Land, it forms a 5–20 m-thick condensed, shallow-marine succession with numerous hiatuses in central and western Spitsbergen (Olaussen *et al.* 2018; Rismyhr *et al.* 2018). Similar thickness trends and hiatuses occur in the SWBS (e.g. Müller *et al.* 2019). It has been suggested that both trends are linked to the tectonism of the Novaya Zemlya Orogen (Klausen *et al.* 2022). By the Toarcian, the variations in thickness were mostly levelled out throughout the archipelago. The upper part of the Wilhelmøya Subgroup is represented by the widespread Toarcian–Bathonian Kongsøya Formation. This formation is highly condensed and dominated by shoreface deposits, commonly separated by offshore sandstones and

shales. The uppermost unit of the Kongsøya Formation is the Bathonian Brentskardhaugen Bed (Fig. 4). It represents a regional transgression and is composed of a polymictic phosphatic conglomerate containing reworked Toarcian–?Bajocian fossils (Bäckström and Nagy 1985; Rismyhr *et al.* 2018). A more detailed description of TSE 5 is available in Supplementary material 3.

TSE 6: Middle Jurassic–Lower Cretaceous Adventdalen Group. The group records other dramatic switches in palaeo-drainage and source area related to uplift in the west and NW of Svalbard, and later volcanic activity in the north and to the east.

Organic-rich shales in the Agardhfjellet Formation (Fig. 4) were deposited on a shallow shelf under variable oxic, dysoxic and anoxic seafloor conditions (Nagy *et al.* 2009). Distal delta-front or lower-shoreface deposits occur within the otherwise shale-dominated unit in western Spitsbergen, recording the initial arrival of sediments sourced from terranes NW and west of Spitsbergen (Dypvik and Zakharov 2012; Koevoets *et al.* 2018). The Slottsmøya Member, the uppermost member of the Agardhfjellet Formation, has recently emerged as one of the world’s richest sources of Jurassic ichthyosaur and plesiosaur fossils (Delsett *et al.* 2016).

The overlying upper Ryazanian/Valanginian–lower Barremian Rurikfjellet Formation forms a 200–300 m-thick coarsening- and shallowing-upward succession (Grundvåg *et al.* 2019; Jelby *et al.* 2020; Śliwińska *et al.* 2020). A basal, condensed glauconitic clay unit – the Myklegardfjellet Bed – formed during maximum flooding of the shelf (Dypvik *et al.* 1992) and represents the onshore equivalent of similar-aged, condensed carbonates of the Klippfisk Formation offshore, whose base is defined by the Base Cretaceous Unconformity (Smelror *et al.* 1998). The lower part of the Rurikfjellet Formation is shale dominated and represents deposition on an open-marine shelf (Grundvåg *et al.* 2017, 2019). Thick successions of gravity-flow deposits occur locally in the NW (Grundvåg *et al.* 2019). The upper part of the formation consists of shallow-marine to deltaic sandstones forming two separate wedges: central and southern Spitsbergen, respectively (Dypvik *et al.* 1991; Grundvåg and Olaussen 2017; Grundvåg *et al.* 2019; Jelby *et al.* 2020).

The overlying up to 120 m-thick fluvio-deltaic succession is assigned to the Barremian–lower Aptian Helvetiafjellet Formation (Fig. 4) (Midtkandal and Nystuen 2009; Grundvåg *et al.* 2017, 2019). The lower part consists of a regionally extensive, cross-bedded sandstone sheet of braided stream affinity (i.e. the Festningen Member), which locally fills incised valleys. The Helvetiafjellet Formation exhibits a transgressive trend, with fluvial deposits in the lower part being overlain by coastal/delta-plain barrier and wave-dominated delta-front sandstones (Nemec *et al.* 1988; Grundvåg *et al.* 2019). The main source area for this fluvio-deltaic system was the exhumed terranes north and west of the SCTSE with depocentres on the shelf further to the south and SE (Gjelberg and Steel 1995; Midtkandal and Nystuen 2009; Grundvåg and Olaussen 2017). A regional provenance switch, however, is documented in the middle part of the formation attributed to the emerging volcanic terrains of the HALIP to the east (Edwards 1979; Maher 2001; Maher *et al.* 2004).

The conformably overlying Carolinefjellet Formation of early Aptian–late middle Albian age is up to 1200 m thick and represents the youngest preserved Mesozoic strata in Svalbard (Fig. 4) (Maher *et al.* 2004; Grundvåg *et al.* 2019, 2020). The base of the formation is defined by a regionally extensive lower Aptian organic-rich shale unit deposited during the final drowning of the retreating Helvetiafjellet Formation delta (Midtkandal *et al.* 2016; Grundvåg *et al.* 2019). The remaining part of the Carolinefjellet Formation was generally deposited

in an open-marine, storm-dominated shelf setting, and consists of alternating inner-shelf sandstone sheets and offshore mudstone units (Grundvåg *et al.* 2020). A more detailed description of TSE 6 is available in Supplementary material 4.

TSE 7: Paleocene–Eocene Van Mijenfjorden Group. The up to 1.9 km-thick Paleogene Van Mijenfjorden Group in the CTB consists of a Paleocene and an Eocene to possibly Early Oligocene succession.

Bentonite (tephra) layers sampled from the Firkanten, Frysjaodden and Basilika formations in the CTB yield U–Pb ages of 61.6, 59.3 and 55.8 Ma, respectively (Charles *et al.* 2011; Jones *et al.* 2017; Jochmann *et al.* 2020). The oldest bentonite bed, at the base of the Firkanten Formation, can be traced laterally for almost 100 km from north to south within the basin (Jochmann *et al.* 2020). Geochemical fingerprinting suggests the Kapp Washington volcanic rocks in North Greenland as the source for the oldest bentonite bed, while the younger beds are likely to represent volcanism in the Nares Strait, Arctic Canada (Jones *et al.* 2016, 2017). The youngest dated bentonite in the CTB has been used to refine the absolute age of the Paleocene–Eocene Thermal Maximum (PETM: Charles *et al.* 2011).

The Paleocene succession accumulated in a fault-bounded basin, and consists of offshore shale (the Basilika Formation) and intercalated sandstone wedges of shallow-marine to paralic origin (i.e. the Firkanten, Grumantbyen and Hollendardalen formations). The paralic lower part of the Firkanten Formation represents the most important coal-bearing unit in Svalbard (Nøttvedt 1985; Lüthje *et al.* 2020).

The Eocene basin fill accumulated in a foreland basin that formed in response to the development of the WSFTB. It represents an overall regressive megasequence comprising several hundred metres of thick basin-floor shale of the Frysjaodden Formation at the base, gradually passing upwards into shallow-marine to deltaic sandstones of the Battfjellet Formation, and eventually alluvial deposits of the Aspelintoppen Formation (Helland-Hansen 2010; Grundvåg *et al.* 2014a; Helland-Hansen and Grundvåg 2020). The Paleocene succession was largely sourced from the east, whereas the overlying Eocene to possibly early Oligocene succession saw a major change to westerly derived sediments in response to the growing WSFTB (Steel *et al.* 1985; Helland-Hansen 1990; Bruhn and Steel 2003; Petersen *et al.* 2016).

Paleogene outliers also occur in several smaller structurally confined basins within the WSFTB (e.g. Blinova *et al.* 2013; Smelror and Larssen 2016; Jochmann *et al.* 2020; Schaaf *et al.* 2021). A more detailed description of TSE 7 is available in Supplementary material 5.

Magmatism

Carboniferous

A vertical NE–SE-striking monchiquite (lamprophyre) dyke occurs at Krosspynten in Wijdefjorden, Spitsbergen (Gayer *et al.* 1966). It is approximately 0.9 m wide, and clearly cross-cuts folded Devonian sandstones and shales. It has a vertically zoned appearance with alternating fine- and coarse-grained crystals, and exhibits vertical and horizontal fractures. Krasil'shchikov (1964) obtained a K–Ar age of 309 ± 5 Ma for the dyke, suggesting a Late Carboniferous basic magmatism (Gayer *et al.* 1966). However, an ongoing study, applying the $^{40}\text{Ar}/^{39}\text{Ar}$ step heating method, indicates an older, possible late Mississippian age for the intrusion (Morgan Ganerød pers. comm. 2019).

Early Cretaceous

In Svalbard, Early Cretaceous mafic rocks related to the HALIP are assigned to the Diabasodden Suite (Dallmann *et al.* 1999; Senger *et al.* 2014a, b), which comprises both doleritic sills and dykes throughout Svalbard, and basaltic lava flows on Kong Karls Land (Smith *et al.* 1976; Bailey and Rasmussen 1997; Olausen *et al.* 2018). The intrusions are emplaced in a wide range of lithologies and stratigraphic intervals. In Spitsbergen, Edgeøya and Barentsøya, they are preferentially located in Triassic shales (early phase of TSE 4), whereas further east (i.e. at Kong Karls Land) they appear in Upper Jurassic shales and Lower Cretaceous sandstones (late phase of TSE 4). U–Pb dating of several sills suggests a short-lived magma emplacement pulse at *c.* 124.5 Ma (Corfu *et al.* 2013). On Kong Karls Land, tholeiitic plateau flood basalts are resting on, or interfingering with, the fluvio-deltaic Helvetiafjellet Formation (which at this location is suggested to be of an Aptian age: Smelror *et al.* 2018), and volcanoclastic material locally occurs in fluvial-channel deposits within the unit (Olausen *et al.* 2018). Ongoing studies using the $^{40}\text{Ar}/^{39}\text{Ar}$ step heating method gave a maximum age for lava flows of 126.1 ± 1.7 Ma (Morgan Ganerød pers. comm. 2020).

Heat flow

The current geothermal gradient and heat flow vary from 25 to 55°C km^{-1} and from 65 to 70 W m^{-2} , respectively (Fig. 7) (Betlem *et al.* 2018). The base of the Paleocene Firkanten Formation in the central parts of the CTB were subjected to temperatures of 120°C , reflecting a geothermal gradient of approximately 50°C km^{-1} in the Eocene–Oligocene. The local variations in geothermal conditions across the archipelago, at least partially, may be explained by the present out-of-equilibrium conditions due to Neogene pre-glacial and glacial loading, unloading, and erosion rates (Lucazeau 2019).

Localized Neogene–Quaternary volcanism reported in northwestern Spitsbergen (Dallmann 2015), fluid migration along pre-existing fault zones and effects from the asthenosphere (e.g. Minakov 2018) may all have contributed to the documented thermal heterogeneity.

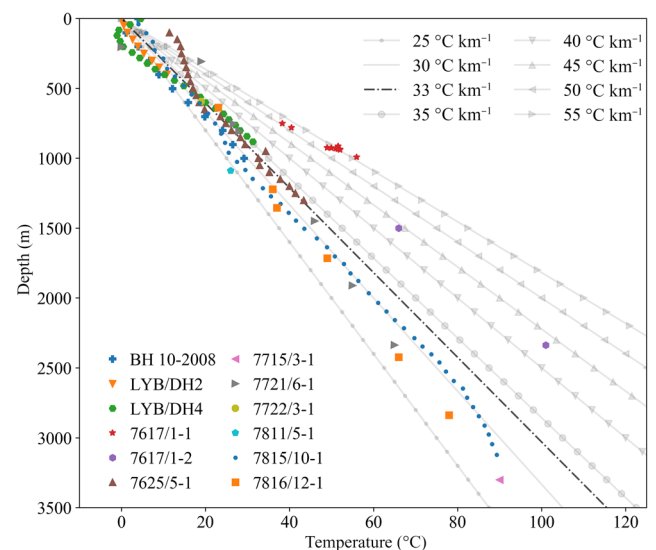


Fig. 7. Temperature gradients from exploration and research wells.

Svalbard CTSE

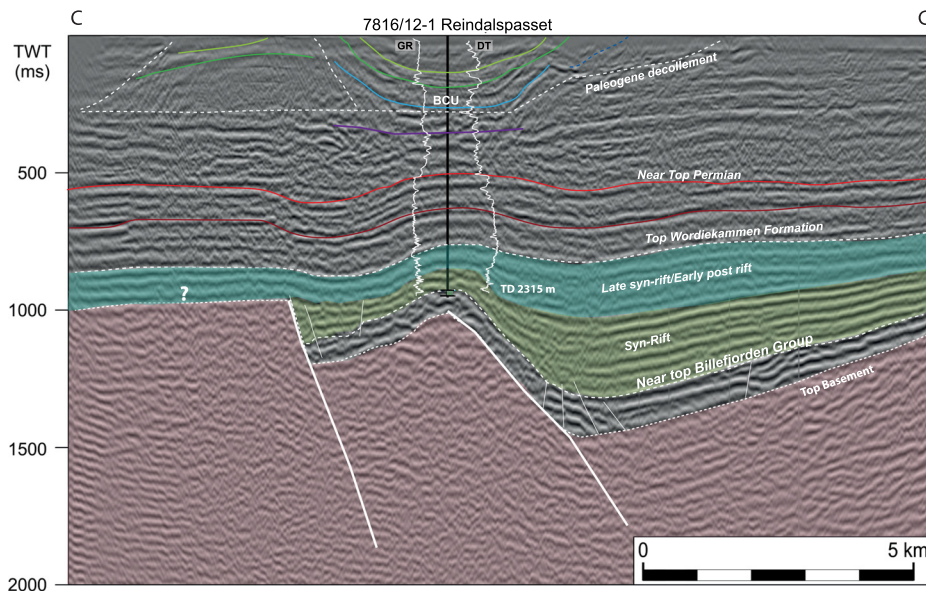


Fig. 8. The only example of a drilled prospect based on subsurface mapping in Svalbard, Reindalspasset, well 7816/12-1. The target was a play with a Pennsylvanian rotated fault block as the trap, and sandstone and carbonates as the reservoir, which were sourced from Mississippian coal and shales. BCU, Base Cretaceous Unconformity (i.e. Base Rurikfjellet Formation); TD, terminal depth; TWT, two-way travel time. Colour legend for the seismic reflectors: brown, intra-Permian reflector; red, near top Permian (i.e. top Kapp Starostin Formation); violet blue, BCU; dark green, Base Helvetiafjellet Formation; light green, base Carolinefjellet Formation. See Figure 4 for the stratigraphy.

Petroleum geology

Discovered and potential petroleum resources

No economic discoveries have been made onshore Svalbard, although small technical discoveries are reported from oil and gas exploration, coal exploration, and scientific drilling (Senger *et al.* 2019). Most drilled prospects in Svalbard were de-risked based on the surface geology, mapping and stratigraphy. The exception to this is the 7816/12-1 Reindalspasset well, which drilled a prospect defined on 2D seismic data (Fig. 8).

Current exploration status

There has been no hydrocarbon exploration in the Svalbard archipelago or the surrounding territorial waters (12 nm from the coastline) since 1995. The very high technical risk of making economic discoveries is combined with several logistical challenges: the remoteness of the high Arctic, strict environmental regulations and numerous protected areas throughout the archipelago. Because of this, any future exploration in the archipelago is inconceivable.

Hydrocarbon systems and plays

Although there are no indications of economically valuable oil or gas accumulations in the SCTSE, unconventional hydrocarbons in the form of shale gas have been proven in the Agardhfjellet Formation in Adventdalen in the vicinity of Longyearbyen, possibly representing a local energy source for the future (Ohm *et al.* 2019). Bituminous-stained sandstones and carbonates occurring in several stratigraphic levels of the SCTSE indicate the presence of multiple source rocks and migration phases that record secondary oil migration and dismigration into previously efficient traps (Fig. 4). Palaeohydrocarbon accumulations sourced from Carboniferous and Lower Permian lacustrine mudstones, coals and carbonates (TSE 1 and TSE 2) have probably been efficiently sealed by mudstones or evaporites in central parts of the archipelago (Nicolaisen *et al.* 2019). Furthermore, recent studies of bitumen-stained Mesozoic sandstones (Abay *et al.* 2017) suggest that oil has migrated from the organic-rich mudstones of the Middle Triassic Botneheia Formation (TSE 5) and the

Middle Jurassic–Lower Cretaceous Agardhfjellet Formation (TSE 6). The first phase of migration from these Mesozoic source rocks and the succeeding accumulation in porous sandstones probably occurred prior to the regional Neogene uplift. This palaeohydrocarbon system is analogous to age-equivalent, prolific plays in the SWBS, where the Steinkobbe and Hekkingen formations act as source rocks. Discovery of non-biodegraded bituminous sandstones in the Lower Jurassic Svenskøya Formation (lower part of TSE 4) on the east coast of Spitsbergen also points to a second, and more recent, migration phase, probably related to late Neogene uplift and erosion (Abay *et al.* 2017). Roy *et al.* (2019) documented ongoing near-shore gas seepage in northern Isfjorden, while Hodson *et al.* (2020) illustrated methane seepage through pingos onshore Nordenskiöld Land. In many places throughout Svalbard, gas accumulations have been trapped at the base of permafrost. At Kapp Amsterdam near Svea, a significant shallow gas accumulation at the base of permafrost was encountered in a terminal moraine that is only 600 years old – also evidence of ongoing hydrocarbon migration at present. The out-of-equilibrium system may also result in hard-to-predict hydrodynamically trapped hydrocarbon accumulations.

A major factor of the hydrocarbon system in the SCTSE is the pore pressure. Due to the out-of-equilibrium conditions, the pore-pressure regimes are diverse throughout Svalbard, ranging from severe underpressure to mild overpressure. While the overpressure can be explained by topography-driven flow or gas buoyancy, the more severe cases of underpressure cannot. The most reliable quantitative pressure data are derived from the Longyearbyen CO₂ Lab boreholes in Adventdalen (Braathen *et al.* 2012; Olausen *et al.* 2019), where long-term pressures were recorded (Birchall *et al.* 2020). Parts of the Mesozoic succession are severely underpressured, with pressures up to 60 bar below hydrostatic recorded in the Wilhemøya Subgroup and in the lower parts of the regional cap-rock unit, the Agardhfjellet Formation (Fig. 4) (Birchall *et al.* 2020). Studies show that this condition formed recently and is in a state of disequilibrium (Wangen *et al.* 2016; Birchall *et al.* 2020). These geologically recent changes in pressure–volume–temperature (PVT) conditions almost certainly promote active ongoing migration (Birchall *et al.* 2020), which is also supported by numerous seeps, flares and shows throughout the archipelago (Senger *et al.* 2019 and references therein).

Source rocks. Source-rock units occur at multiple stratigraphic levels within the SCTSE (Fig. 4). Below follows an

overview of the most important and relevant source-rock units, particularly those relevant for exploration in the SWBS.

Carboniferous and Permian (TSE 1–TSE 4). Organic-rich mudstones and coals in the Billefjorden (TSE 1) and Gipsdalen (TSE 2 and TSE 3) groups are proven potential source rock units in central Spitsbergen (van Koeverden *et al.* 2011; Nicolaisen *et al.* 2019). A normal distribution of T_{\max} of 440°C suggests maturation in the late oil window (Nicolaisen *et al.* 2019). Coaly mudstones and organic-rich floodplain deposits to lacustrine mudstone in the Mississippian Billefjorden Group in central Spitsbergen have reported total organic carbon (TOC) values of 11–28 wt%, and a hydrogen index (HI) of *c.* 160–350 mgHC g⁻¹ TOC, and a mixture of Type II and III kerogen. These fine-grained organic-rich units might add up to *c.* 100 m in cumulative thickness. The interbedded coal seams yield both gas and oil (Abdullah *et al.* 1988; van Koeverden and Karlsen 2011).

Organic-rich marine calcareous mudstones in the Gipsdalen Group occur as either thin beds intersecting carbonates or evaporites, or as a thicker (up to 10 m) unit of fusulinid-rich shaly limestone: the Lower Permian Brucebyen Bed (Nicolaisen *et al.* 2019). The thin interbeds have an average TOC of 1–10 wt% and HI values of 200–400 mgHC g⁻¹ TOC. The beds seldom reach a thickness above 30–40 cm but might add up to *c.* 10 m in the Minkinfjellet and Gipshuken formations. In comparison, the Brucebyen Bed reach an average TOC of 2.4 wt% and a HI index ranging from 100 to 350 mgHC g⁻¹ TOC (Nicolaisen *et al.* 2019), thus forming the most significant source rock in the Gipsdalen Group.

Mesozoic (TSE 5 and TSE 6). The two most important regional source rocks in the SCTSE are the organic-rich marine mudstone (OMM) from the Middle Triassic Botneheia Formation (TSE 5) and the Middle Jurassic–Lower Cretaceous Agardhfjellet Formation (TSE 6). Their offshore near time-equivalent counterparts, the Steinkobbe and Hekkingen formations, respectively, are both known to charge numerous fields in the Norwegian Barents Sea (Leith *et al.* 1993; Ohm *et al.* 2008; Henriksen *et al.* 2011b; Abay *et al.* 2018). Both the Botneheia and Agardhfjellet formations were deposited in relatively shallow shelf waters, periodically under anoxic seafloor conditions, in distal pro-deltaic settings in front of large, prograding delta systems (Glørstad-Clark *et al.* 2011; Anell *et al.* 2014a, c, 2016; Koevoets *et al.* 2018; Wesenlund *et al.* 2022). Bitumen in Mesozoic sandstones from outcrops and cored boreholes indicate that both OMM units were once active source rocks (Abay *et al.* 2017). The maturation of the Mesozoic OMM within the SCTSE records a west–east trend from burned out/overmature in the SW to late oil window in the west via peak oil window in central parts to immature in the east. The same trend is seen in the sandstone diagenesis from tight in the west and south to unconsolidated Mesozoic sand on Kong Karls Land to the east. These trends are shown in Figure 9. Local intrusive Cretaceous volcanic rocks may influence this trend (Senger *et al.* 2013; Brekke *et al.* 2014; Olausen *et al.* 2018).

The Botneheia Formation ranges from 80 to 160 m in thickness, and contains dominantly kerogen type II in its upper part and type III in its lower part, with TOC values ranging from *c.* 1 to 11 wt%, with the Blanknuten Member in the upper part of the formation exhibiting the highest organic content (Mørk and Bjørøy 1984; Krajewski 2013; Wesenlund *et al.* 2021, 2022). On NW Edgeøya and south Barentsøya, this part of the formation is in the oil window (Fig. 9) and is an excellent potential oil-prone source rock with *q* median TOC value of 8.10 ± 1.06 wt% and a HI value of 538 ± 42 mgHC g⁻¹ TOC (Wesenlund *et al.* 2021). This upper member is also

typically rich in phosphate, suggesting an influence from upwelling and subsequent high rates of primary production, which eventually promoted oxygen deficiency in the water column (Krajewski 2013; Wesenlund *et al.* 2021). Integrated geochemical studies by Wesenlund *et al.* (2021, 2022) suggest that the lower part of the Botneheia Formation is expected to generate mixed oil and gas (during conditions equivalent to peak oil generation) with relatively greater amounts of saturated *v.* aromatic hydrocarbons compared to the oil-prone, phosphate-bearing upper part of the unit.

In western Spitsbergen, 20–30 m-thick OMM in the lower part of the Bravaisberget Formation (Fig. 4) is correlative with the Botneheia Formation and may locally hold some source potential (Mørk *et al.* 1999).

The Agardhfjellet Formation is an up to 240 m-thick Bathonian–Ryazanian organic-rich mudstone-dominated formation containing >100 m-thick OMM (accumulative) with a TOC that ranges from 2 to 15% (Hvoslef *et al.* 1986; Leith *et al.* 1993; Koevoets *et al.* 2018; Ohm *et al.* 2019).

Core data from Adventdalen, central Spitsbergen, show that the formation contains a mixture of type II and type III kerogen, a TOC of 6–10% and a HI of 50–200 mgHC g⁻¹ TOC. T_{\max} varies from 275 to 455°C in the black paper shale in the lower part of the Agardhfjellet Formation (Koevoets *et al.* 2016). In the east, the formation is largely missing due to erosion related to Late Jurassic and Early Cretaceous inversion (Grogan *et al.* 1999). However, the lowermost part is immature, with vitrinite reflectance values (VR) of 0.38 to 0.42%, a T_{\max} of 410°C and TOC values of up to 40% (Olausen *et al.* 2018).

Another regionally extensive organic-rich mudstone unit with some source potential occurs in the basal part of the lower Aptian–middle Albian Carolinefjellet Formation (uppermost TSE 4; Fig. 4) on Spitsbergen (Midtkandal *et al.* 2016; Grundvåg *et al.* 2019). This 5–30 m-thick potential source-rock unit accumulated during a regional transgression of the underlying delta plain of the Helvetiafjellet Formation in the early Aptian and was evidently influenced by a global oceanic anoxic event (OAE1a) (Midtkandal *et al.* 2016; Zhang *et al.* 2021). Analyses of core material from central Spitsbergen indicate that this unit is dominated by kerogen type III with TOC values up to 2.1 wt% and a HI of 180 mgHC g⁻¹ TOC (Grundvåg *et al.* 2019). An Aptian source-rock unit is proven in the SWBS but here is a potential for oil generation (Hagset *et al.* 2022).

Paleogene (TSE 7). The Paleogene succession in central and western Spitsbergen holds good potential for oil- and gas-prone source rocks, primarily due to the abundance of thick coal seams in the Firkanten Formation (Orheim *et al.* 2007; Marshall *et al.* 2015; Uguna *et al.* 2017). Because of past and ongoing mining, the Paleocene coals have received considerable attention. Maceral analysis of the Firkanten Formation coals document type III kerogen (whereas van Krevelen equivalent diagrams show plots between II and III kerogen) and HI values ranging between 151 and 410 mgHC g⁻¹ TOC (Uguna *et al.* 2017). Distillation of coal yields up to 28% crude oil from pure coal (Orvin 1934), whereas recent analysis by hydrous pyrolysis showed a bitumen yield of up to 320 mg g⁻¹ TOC (Marshall *et al.* 2015). The bitumen has thus migrated, enriching the upper parts of the investigated coal seams and in part the immediate overlying sandstone (Marshall *et al.* 2015). The coals represent thick accumulations of marine-influenced peat deposits, and have better source-rock potential and oil-generating properties than the closely associated organic-rich floodplain deposits. The coal-bearing strata have locally significant amounts of gas, which were regularly encountered as a hazard during coal

Svalbard CTSE

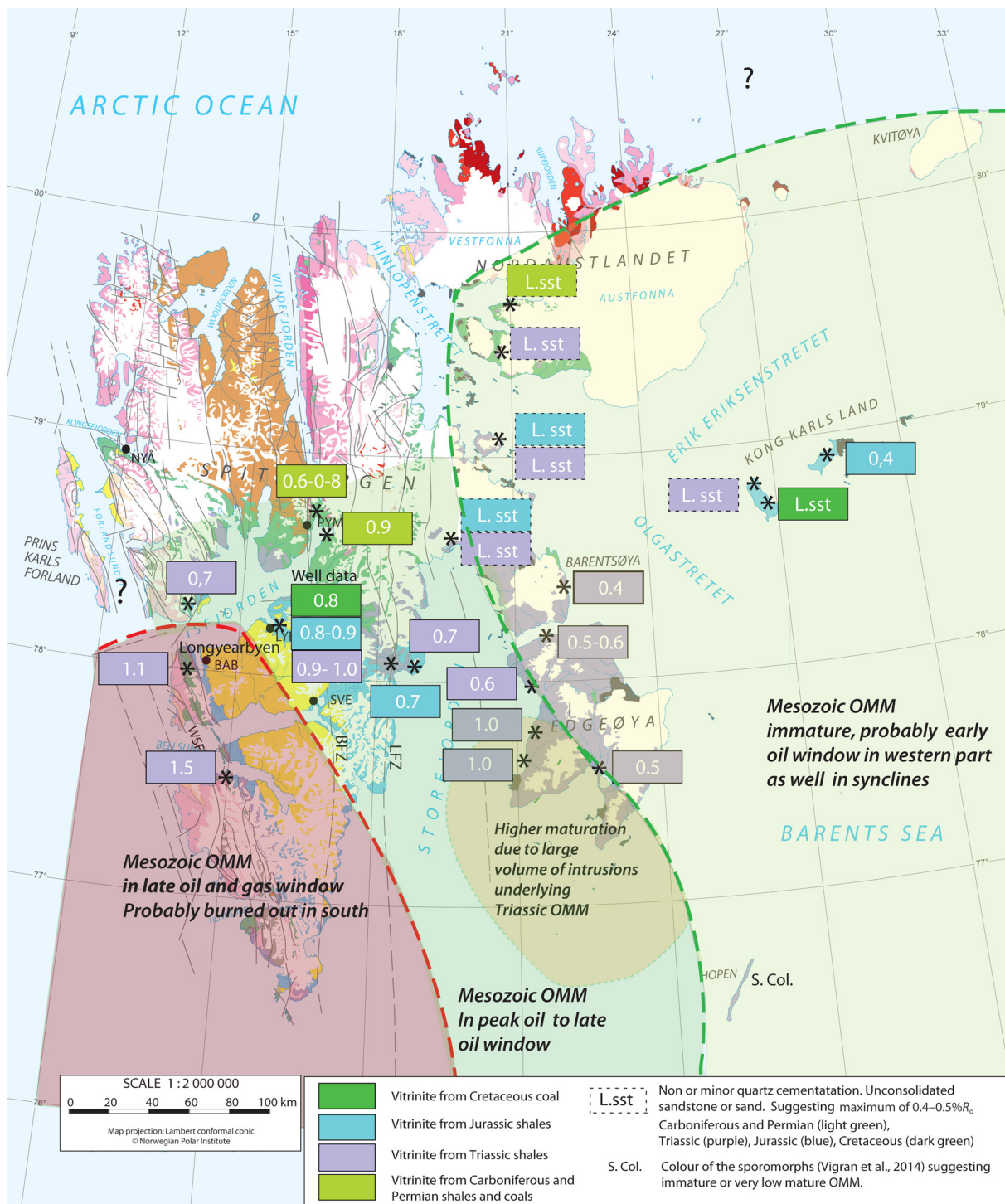


Fig. 9. Maturation trend of Mesozoic organic-rich marine mudstone (OMM) based on the available vitrinite, T_{max} , geochemistry data for bitumen (Mørk and Bjørøy 1984; Abay *et al.* 2017; Ohm *et al.* 2019) and the degree of diagenesis of sandstones (Mørk 2013; Haile *et al.* 2018, 2021), degree of quartz cementation v. maturation (cf., Walderhaug 1996; Bjørlykke and Jahren 2015). Source: geological map from the Norwegian Polar Institute.

exploration drillings in the past, thus representing risk-management challenges to the local mining industry.

Reservoirs. Potential reservoir rocks occur in several of the TSEs described in this study, spanning the Lower Carboniferous (TSE 1) through the Mesozoic (TSE 4) to the Paleogene successions (TSE 5). Based on maturation trends of organic-rich mudstones or coal, the porosity and, in part, the permeability trends of the Upper Paleozoic and Mesozoic sandstones are predictable. The highly diverse reservoirs range from unconventional reservoir units consisting of

fractured tight sandstone in the west (e.g. previously deeply buried below the CTB) to poorly unconsolidated sandstone and unconsolidated sand in the easternmost areas (Mørk 2013; Haile *et al.* 2018; Olausen *et al.* 2018). Upper Carboniferous–Permian carbonate and silica-rich deposits (TSE 3 and TSE 4) are less predictable in an east–west trend, and are largely dependent on the depositional environment, the chemical history of the fluids (related to the burial and uplift history), karstification and dolomitization (Stemmerik and Worsley 1995; Ehrenberg *et al.* 2001; Blomeier *et al.* 2009; Sorento *et al.* 2020). Triassic sandstones (TSE 4) in the east potentially exhibit moderate porosities (12–18%) but low

permeabilities due to poor sorting, immature mineralogy, pore-filling clay minerals and common carbonate cementation.

Carboniferous–Permian (TSE 1–TSE 4). In TSE 1, potential reservoir rocks include various alluvial/fluviol to lacustrine and paralic sandstone units of the Billefjorden Group. The sandstone/shale ratio is highly variable, typically ranging from 0.2 to 0.5. However, higher values are recorded in sandstones up to 100 m thick in the area around the Billefjorden Trough and in the >700 m-thick Orustdalen Formation in west Spitsbergen.

The distribution of reservoir units in TSE 2 is best documented in the Billefjorden Trough. Individual reservoir bodies are typically 10–12 m thick, consisting of fine- to coarse-grained sandstones of paralic origin, and include meandering fluvial-channel fills and braidplain deposits overlain by shoreline and delta-front sandstone units and alluvial fans banked to the master faults (Johannessen and Steel 1992; Braathen *et al.* 2011; Smyrak-Sikora *et al.* 2019).

Potential carbonate reservoir units include >10 m-thick oolitic grainstone units of the Minkinfjellet Formation, which occur along the basin margins and accumulated during the final phase of rifting. Secondary breccias linked to a later event of evaporite dissolution also hold some reservoir potential (Eliassen and Talbot 2005).

The platform carbonates of the Gipsdalen Group have good visible porosity (Ahlborn and Stemmerik 2015). The best porosity, up to 20%, is recorded in carbonate build-ups of localized distribution and considerably less rock volume than in their offshore counterpart in the Ørn Formation in the SWBS (Larssen *et al.* 2002). In the middle part of TSE 3, corresponding to the Gipshuken Formation (Figs 4 & 9), good visible vuggy, mouldic and cavernous porosity is present in the platform carbonates, and dissolution breccias can be traced laterally for several kilometres, in amongst others in the Lomfjorden area. Petrographical analyses have documented both inter- and intra-particle porosities of 15–17% in grainstones and intra-crystalline porosity of 20% in dolomites. The porous platform units are sheet like and persist laterally over several kilometres. The Upper Permian, spiculitic, part of TSE 3 has undergone a complex diagenetic transformation that locally resulted in units with porosities (at best) of up to 12–25% and permeabilities of up to 100 mD (Ehrenberg *et al.* 2001; Matysik *et al.* 2017). Localized Upper Permian glauconitic sandstones occurring along the basin margin may hold some potential, as they are sporadic and seen as partly unconsolidated.

Triassic–Middle Jurassic (TSE 5). The Lower Triassic Vardebukta Formation in the eastern part of the SCTSE features an upwards-coarsening parasequence that terminates in a series of upper-shoreface to fluvial-channel units that may provide good reservoir properties (Mørk *et al.* 1982).

The key Triassic reservoir interval occurs in the De Geerdalen Formation. The sandstone/shale net-to-gross (N/G) of the De Geerdalen Formation (and the age- and facies-equivalent Snadd Formation offshore) increases significantly to the east and SE throughout the SCTSE, reflecting more proximal settings in those directions. Hopen is a key area in highlighting the nature of the Late Triassic reservoir interval throughout the SCTSE and its equivalent units in the Barents Sea (Klausen and Mørk 2014). The well-preserved fluvial-channel-fill sandstone bodies are prominently exposed in the steep cliff sides of the island. Whilst these are relatively isolated in their stratigraphic position and are encased in a highly heterolithic succession, they clearly indicate the presence of relatively good reservoir-quality rocks in the region (Lord *et al.* 2014, 2017).

The Wilhelmøya Subgroup is the onshore analogue to the most prolific hydrocarbon reservoir in the SWBS (i.e. the Realgrunnen Subgroup: Worsley 2008). On Spitsbergen, the Wilhelmøya Subgroup forms a thin Norian–Bathonian condensed paralic sandstone unit, typically <20 m thick, ‘tight’ sandstone and with numerous hiatuses (Bäckström and Nagy 1985; Rismyhr *et al.* 2018:). This subgroup has been suggested to be a potential CO₂ storage unit, forming an unconventional reservoir that relies on a permeable fracture system (Braathen *et al.* 2012; Ogata *et al.* 2012, 2014; Senger *et al.* 2015; Mulrooney *et al.* 2018; Olausen *et al.* 2019).

In the eastern SCTSE (i.e. Kong Karls Land), the Wilhelmøya Subgroup thickens to *c.* 200 m. Here, the reservoir sandstones are poorly consolidated, occasionally occurring as loose sand, and appear to be porous and permeable (Olausen *et al.* 2018). The preserved strata are comparable to the age- and facies-equivalent Realgrunnen Subgroup offshore. The Flatsalen Formation, which is partly analogous to the Fruholmen Formation offshore, has no reservoir potential in Spitsbergen but may hold some potential in eastern Svalbard, with a 0.2–0.3 N/G sandstone/shale ratio. The overlying amalgamated 12–30 m-thick channelized Norian–Rhaetian part of the Sjøgrenfjellet Member of the Svenskøya Formation in Kong Karls Land and Hopen has good reservoir potential with an estimated sandstone/shale ratio of 0.9–1 (Lord *et al.* 2019). The remaining part of the heterolithic deposits of the Hettangian–lower Pliensbachian Sjøgrenfjellet Member shows a variation in the sandstone/shale ratio, ranging from 0.5 to 0.7.

The 20–50 m-thick upper Pliensbachian–upper Toarcian Mohnhøgda Member of the Svenskøya and the upper Toarcian–Aalenian Kongsøya Formation shows a sandstone/shale ratio that ranges from 1 in central Spitsbergen to 0.7–0.8 in the east. On the islands of Kong Karls Land, sandstones of the Kongsøya Formation shale-out towards the east (i.e. from Kongsøya to Svenskøya). This also indicates a prominent palaeodrainage shift towards a source located more to the east.

Middle Jurassic–Lower Cretaceous (TSE 6). In western Spitsbergen, the Kimmeridgian Oppdalsåta Member of the Agardhfjellet Formation comprises four or five 10–15 m-thick shallowing-upward sequences with a sandstone/shale ratio ranging from 0.3 to 0.5 and visible porosity (Koevoets *et al.* 2018).

In southern Spitsbergen, the Valanginian–Barremian Rurikfjellet Formation may offer some reservoir potential, as its upper part contains a *c.* 150 m-thick succession of stacked coarsening-upward delta-front units. This succession appears to continue southwards into the offshore area of the SCTSE (Grundvåg and Olausen 2017). We estimate that the sandstone/shale ratio of this succession in the south ranges from *c.* 0.5 in its lower part to 0.8 in its upper part.

One of the most prominent sandstone units in Spitsbergen and Kong Karls Land is the fluvio-deltaic Barremian–Aptian Helvetiafjellet Formation (Fig. 4). The thickness of the unit varies from 45 to >150 m, reflecting deposition within large-scale incised valleys (Gjelberg and Steel 1995; Midtkandal *et al.* 2008; Midtkandal and Nystuen 2009; Olausen *et al.* 2018; Grundvåg *et al.* 2019), as well as syntectonic movements in the Barremian (Nemec *et al.* 1988; Onderdonk and Midtkandal 2010). The lowermost sandstone unit, the Festningen Member, is a regionally extensive 5–15 m-thick cross-bedded sandstone sheet of braidplain origin. The sandstone/shale ratio is generally high, ranging from 0.6 to 0.9.

Despite low porosities of 6–8% in central Spitsbergen, measured permeabilities are remarkably high (*c.* 80–100 mD) as demonstrated by aquifer flow from this interval during drilling of the Longyearbyen CO₂ Lab (Braathen *et al.* 2012) and in

numerous coal exploration boreholes in the Longyearbyen vicinity. The overlying Carolinefjellet Formation contains some sandstone-dominated intervals of mostly shallow-marine origin (Grundvåg *et al.* 2020). However, their reservoir potential is strongly hampered by early diagenetic calcite cementation (Maher *et al.* 2004) and various carbonates precipitated during deeper burial.

Paleogene (TSE 7). In TSE 7, the nearly 2 km-thick Van Mijenfjorden Group in the CTB (Fig. 4) contains several units with reservoir potential, although visible porosity is generally very low.

The lowermost reservoir unit is the 100–170 m-thick Firkanten Formation (Paleocene) that exhibits both shoestring and sheet-like reservoir bodies deposited in a paralic depositional environment. There is an upward increase in the N/G ratio corresponding to a transition from a heterolithic fluvial succession in the lower part to shoreface sandstones with a N/G ratio of 0.9 in the upper part. The Hollendardalen Formation (uppermost Paleocene–lowermost Eocene) forms an up to 150 m-thick, eastward-thinning tidally influenced deltaic wedge confined to the western margin of the CTB. Internally, the wedge is organized into *c.* 10 m-thick coarsening-upward units with a particularly high sandstone/shale ratio in their upper parts.

The Battfjellet Formation and the overlying Aspelintoppen Formation (Eocene to possibly Oligocene?) also hold some reservoir potential. The main reservoir bodies of the Battfjellet Formation comprise a series of shingled, shallow-marine to deltaic units representing a southeastward-prograding shelf-prism clinoform system (Grundvåg *et al.* 2014a; Helland-Hansen and Grundvåg 2020). Sandstone-rich turbidite deposits (with high N/G ratios) encased in basin-floor mudstones (i.e. the Frysjaodden Formation) may offer the possibility of stratigraphic traps (Grundvåg *et al.* 2014b; Spychala *et al.* 2021). Reservoir units of the Aspelintoppen Formation consist of ribbon-shaped fluvial-channel sandstone bodies and crevasse splay units encased in overbank fines (Grundvåg *et al.* 2014a).

Seals. Conventional seals are offered by Paleozoic carbonates and evaporites, thick black shales in the Triassic–Jurassic, and silty shales in the Cretaceous–Paleogene (Fig. 4) (Nøttvedt *et al.* 1993). The sealing capability of potential sealing rocks in the SCTSE is complicated by their laterally heterogeneous nature and recent uplift.

The sequence of the Hekkingen and Fuglen formations provides the most important cap rock in the Barents Sea (Ohm *et al.* 2008; Paulsen *et al.* 2022). In Svalbard, the Agardhfjellet Formation forms a time-equivalent cap rock; this is fully cored by four research boreholes of the Longyearbyen CO₂ Lab in Adventdalen, and has previously been characterized in terms of sedimentology, mineralogy and geochemistry (Koevoets *et al.* 2016, 2018; Abay *et al.* 2017; Ohm *et al.* 2019).

The rheological impacts of Cenozoic uplift may be profound in cap-rock effectiveness. Previous deep burial has left the potential seals mechanically and chemically overcompacted for their present-day depths. This may enhance some mechanical properties, as is evident from the extremely high leak-off pressures in the Fuglen Formation offshore (Paulsen *et al.* 2022), often more than the lithostatic pressure. Conversely, it may also make the cap rock more prone to brittle failure, with fault zones being a particular risk (Paulsen *et al.* 2022).

Additional possible seals may be offered by faults, igneous intrusions, diagenetic tight sedimentary rocks, evaporites, permafrost and associated gas hydrates (Senger *et al.* 2013; Mulrooney *et al.* 2018; Betlem *et al.* 2019). In particular, permafrost appears to be an efficient shallow seal, as is evident

from the thermogenic gas found trapped immediately below the permafrost during several drilling operations in Svalbard.

Migration is obviously ongoing in at least central and eastern parts of Spitsbergen, and is likely elsewhere, as demonstrated by numerous active seeps and flares (Abay *et al.* 2017). The occurrence of a large gas accumulation (and blow-out) below permafrost in moraine sediments that are 600 years old at Kapp Amsterdam also provides evidence of ongoing migration.

Traps. The diverse tectonic history of the SCTSE has resulted in the formation of many potential trapping mechanisms. From extensional faulting in the Paleozoic, producing half-graben or rollover structures, to numerous compression and transpression events, resulting in large gentle anticlines in addition to regional decollement zones (e.g. Nøttvedt *et al.* 1993).

Acknowledgements This review of the Svalbard Composite Tectono-Sedimentary Element is based on many previous works, particularly those led and initiated by the former Harland Group at Cambridge University (UK), and by the research groups at the Norwegian universities in Oslo and Bergen led by David Worsley and Ron Steel, respectively. We thus acknowledge the hard work of previous investigators and are grateful for the framework on which our studies have largely been built. In the 1990s and onwards, research programmes were mostly sponsored by the oil industry, and much of the work presented here would not have been possible without their support. Bjørn Lundschie, Alf Ryseth and Morten Smelror and the editors are gratefully acknowledged for comments that improved the manuscript.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions **SO:** supervision (lead), writing – original draft (lead), writing – review & editing (lead); **S-AG:** writing – original draft (equal), writing – review & editing (equal); **KS:** writing – original draft (equal), writing – review & editing (equal); **IA:** writing – original draft (supporting), writing – review & editing (supporting); **PB:** writing – original draft (supporting), writing – review & editing (supporting); **TB:** writing – original draft (supporting), writing – review & editing (supporting); **AB:** writing – original draft (supporting), writing – review & editing (supporting); **WD:** writing – original draft (supporting), writing – review & editing (supporting); **MJ:** writing – original draft (supporting), writing – review & editing (supporting); **EPJ:** writing – original draft (supporting), writing – review & editing (supporting); **GL:** writing – original draft (supporting), writing – review & editing (supporting); **AM:** writing – original draft (supporting), writing – review & editing (supporting); **PTO:** writing – original draft (supporting), writing – review & editing (supporting); **AS-S:** writing – original draft (supporting), writing – review & editing (supporting); **LS:** writing – original draft (supporting), writing – review & editing (supporting).

Funding This work was funded by the Research Council of Norway, which financed the Longyearbyen CO₂ Lab, Triassic North (grant no. 234152 awarded to AB), and the ongoing ARCEX (grant no. 228107 to S-AG) and the Suprabasins (grant No. 295208 awarded to AB) projects. Also funded by the industry sponsored Locra/Julocra project awarded to A. Escalona and SO.

Data availability Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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