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The Svalbard Carboniferous to Cenozoic Composite Tectono-Stratigraphic Element

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Abstract

The Svalbard Composite Tectono-Stratigraphic Element is located on the north-western corner of the Barents Shelf and comprises a Carboniferous to 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 to 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 most of the Late Cretaceous and early Danian throughout the Svalbard Composite Tectono-Stratigraphic Element. 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 Palaeogene. This event was followed by formation of yet another major hiatus spanning the Oligocene to Pliocene. Multiple reservoir and source rock units are exposed in Svalbard providing analogues to the offshore prolific offshore acreages in southwest Barents Sea and are important for de-risking of plays and prospects. However, the archipelago itself is regarded as high-risk acreage for petroleum exploration. This is due to Palaeogene contraction and late Neogene uplift of particularly the western and central parts. In the east there is an absence of mature source rocks, and the entire region is subjected to strict environmental protection.

Introduction

Located at the north-western corner of the Eurasian continental plate, 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 particularly, the rocks in Svalbard record the events related to the opening of the NE Atlantic and the Arctic oceans. The Carboniferous to 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 to Mesozoic platform successions, the structural evolution of Svalbard differs slightly 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 first 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. But Svalbard's outcrops have nonetheless been instrumental in training petroleum geologists from Norway and abroad to better decipher the petroleum system elements and improve understanding of other parts of the Norwegian Continental Shelf.

In the Svalbard Composite Tectono-Stratigraphic 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 combination with the numerous protected natural areas throughout the archipelago and adjacent nearshore areas, Svalbard does not hold the technical potential to become a future oil and gas province.

Contrary to 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 ca. 78 million metric tons of Paleocene and ca. 9 million metric tons Mississippian coal being 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 to Paleogene sedimentary rock succession and its associated structural elements. As such, the underlying economic basement consisting of Devonian and older sedimentary rocks, as well as Precambrian igneous and metamorphic rocks, are not considered.

1. Age.

Carboniferous – Paleogene. The Carboniferous to 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 & Worsley, 1984, Jochmann et al., 2021). 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).

2. Geographic location and dimensions

The Svalbard archipelago which includes all island between 71 and 81°N and 10 and 35°E and is bounded in the west and north by Cenozoic passive continental margins facing the NE Atlantic and Arctic oceans, respectively (Fig 1A) (Faleide et al., 2008; Piepjohn et al., 2016). Nearly 60% of the exposed landmasses of 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 1700m 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 of 50–150 m water depths), whereas most of the larger fiords tend to be deeper, recording a significant deepening in their outer parts (e.g., outer Isfjorden: >400 m deep). The SCTSE (FIG 1A, B) is located between approximately 76°N to 80°N and 12°E to 30°E and covers an area of ~121 000 km^2.

3. Principal data sets

The principal data sets used and reviewed in this paper include large amount 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 location of wells and seismic lines is shown in Figure 2.

Outcrops

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 summarised by a series of geological maps published by the Norwegian Polar Institute (NPI) and in numerous articles and books (e.g., Steel & Worsley, 1984; Harland, 1997; Dallmann, 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., 2020). The efforts by previous investigations thus form the framework for this paper.

Research, coal, and petroleum exploration 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 to 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) 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 fiords, 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), Grogan et al. (1999, 2000), Anell et al. (2014a, b, c), Bergh et al. (1997), Johannessen et al. (2011), Blinova et al. (2012), Senger et al. (2013), Roy et al. (2015).

Six of the exploration wells (Reindalspasset, Colesbukta, Kapp Laila, Vassdalen II and III, Ishøgda) and two research boreholes (Sysselmannbreen, DH 2, DH4) can be tied to 2D seismic data (Fig. 3). Only the prospect in the Reindalspasset well 7816/12-1 was drilled based upon sparse 2D acquisition and limited seismic mapping and tested a conventional play model (see chapter 10).

Other geophysical data.

Gravity and magnetic data have been acquired and compiled by the Geological Survey of Norway and 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 have been acquired to characterize the geothermal potential of Nordenskiöld Land (Beka et al., 2016; 2017a) and Brøggerhalvøya (Beka et al., 2017b), and provide additional constrains on the regional tectonic structure of the area through subsurface conductivity profiles.

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

The Carboniferous to Cenozoic evolution of the SCTSE includes a series of tectonic events grouped into seven separate tectono-stratigraphic elements (TSE 1 - TSE 7). IT should be noted that this is an oversimplification of the complexity of tectonic/erosional/depositional phases recorded in Svalbard and nearby offshore area. The main tectonic events, lithostratigraphic sub-division of the investigated succession, and the hydrocarbon play elements are summarised in Figure 4.

The western boundary of the SCTSE is bounded along the eastern margin of the highly deformed WSFTB which locally includes over thrusted Precambrian to Paleogene successions. The inverted Carboniferous Capria Ridge and southern rim of the Hopen High (Anell et al., 2016) mark the southern edge of SCTSE (Fig. 1A). The Carboniferous and partly Permian are mainly fault bounded to basement in the north and north-east which defines the northern boundary of the SCTSE. Elsewhere the northern boundary is defined by the last outcropping Carboniferous to Paleogene strata overlying the economic basement. Initial subsidence during the earliest Mississippian promoted the development of a Tournaisian to Visean 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 syn-kinematic structural regime. Extensional basins are suggested in southern and western part of Spitsbergen (Cutbill & Challinor, 1965; Holliday

& Cutbill, 1972; Gjelberg & Steel, 1981; Braathen et al., 2011, Maher & Braathen, 2011; Smyrak-Sikora et al., 2018; 2021).

The Late Mississippian to Middle Pennsylvanian rifting resulted in the formation of a series of elongated, N–S oriented fault bounded basins on Spitsbergen (McCann & Dallmann, 1996; Braathen et al., 2011; Bælum & Braathen, 2012, Maher & Braathen, 2011; Smyrak-Sikora et al., 2018; 2021). This syn rift tectonic stratigraphic 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 through 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 & 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 to Triassic development of the North Atlantic rift system along the western margin of the Barents Sea and East Greenland (Riis et al., 2008; Clark et al., 2014; Seidler et al. 2004; Anell et al. 2016; Tsikalas et al., 2021). A cool-water carbonate platform developed during this syn rift 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.

Early Triassic to Middle Jurassic regional subsidence resulted in the development of a sag basin dominated by siliciclastic deposition (TSE 5; Fig. 4). The Middle Triassic to Upper Triassic northwest 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). Also a less prominent western source contributed to deposition in the western and southern part of the SCTSE (Mørk et al., 1982; Krajewski & Weitschat, 2015; Czarniecka et al., 2020). A condensed Norian to Pliensbachian succession, is less than 10 m thick and with numerous internal hiatuses in the west thickens eastwards to a more than 200 m thick, stratigraphically almost complete succession (Fig. 4). The eastern succession of TSE 5 is attributed to the development of a foreland basin linked to the Novaya Zemlya orogen (Olaussen et al., 2018; Müller et al., 2019).

Late Middle Jurassic to Early Cretaceous regional subsidence with uplift in the north and northwest 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 onwards from the Barremian (Maher 2001; Grantz et al. 2011; Polteau et al., 2015). Local extensional faulting occurred on Spitsbergen (Onderdonk & Midtkandal,

2010) and some minor contraction took place in the east, at Kong Karls Land and Platform (Grogan et al., 1999; 2020; Olaussen et al., 2018).

The latest middle Albian to latest Danian hiatus records exhumation of the entire SCTSE with a significant component of northerly uplift, probably induced by magmatism and opening of the Amerasian Basin north of Svalbard (Maher, 2001). Plate tectonic reorganisation initiated by the opening of the north Atlantic may also have contributed to the uplift and the development of this major hiatus (e.g. Faleide et al., 2010). 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 & Larssen, 2016).

North-directed opening of the North-Atlantic culminated with 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 Palaeocene, 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 & Grundvåg, 2020). The foreland basin fill is assigned to the 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 to Oligocene indicates a shift from transpression to transtension driven by changes in plate motion (Maher et al., 1997; Braathen et al., 1999; Maher et al., 2020).

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 onset of oceanic spreading close to western Spitsbergen probably governed the development of a Neogene hiatus across the Svalbard archipelago and surrounding shelf areas (Green and Duddy, 2010). Particularly the central and western parts of the archipelago and north-western part of the Barents Shelf margin have been subjected to significant uplift during the last few million years (Dimakis et al., 1998, Henriksen et al., 2011b; Lasabuda et al., 2018), and presence of thick pre-glacial (probably Miocene and Pliocene) and glacial (late Pliocene and Pleistocene) clastic wedges offshore west Spitsbergen (Hjelstuen, 1996) suggests net denudation of approximately 3 km (Riis & Fjeldskaar, 1992). This is in overall agreement with uplift estimates in the range 2.5-3.5 km based on organic geochemical studies (Throndsen, 1982; Marshall et al., 2015; Olaussen et al., 2019). However, the westernmost margin of the SCTSE might be subjected to higher magnitude of uplift or a higher temperature gradient. Remnants of Pleistocene glacial deposits occur locally onshore Spitsbergen, indicating multiple glaciations (Ingólfsson & Landvik, 2013)

5. Underlying and overlying rock assemblages

The oldest crystalline basement rocks in Svalbard are dated to 2709 ±28 Ma (U-Pb zircon ion microprobe; Hellman et al., 2019). The youngest rocks below SCTSE are of Fammenian in age. Tournaisian to Visean strata exhibit a meta sedimentary 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 reached drilled into carbonate beds of disputed age, possibly being of either Late Devonian or Silurian to Ordovician age at a total drilling depth (TD) of 2283m) (cf. Harland & 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 similar to that proven in the onshore areas (Faleide et al., 2017).

6. Subdivision and internal structure

One of the main structural characteristics of 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 N-S rift basin is the Billefjorden Trough between Billefjorden and Austfjorden (Fig 1B). It is a ca. 25 km wide, westward dipping and southwards plunging half-graben with the main extensional phases during the Serpukhovian to Moscovian (Maher & Braathen, 2011; Smyrak-Sikora et al., 2018; 2021). The preserved basin fill forms a westward thickening wedge, up to 2 km thick on the hanging wall of the N-S 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 N- S 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 N-S striking basement dominated high; the Ny Friesland High (Fig. 1B, 6). We speculate that the Ny Friesland High is a Carboniferous horst structure and that the Lomfjorden Trough represent the remnants of a larger Carboniferous graben (Fig. 6).

Permian reactivation

Reactivation of the N-S 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 to uppermost Permian deposits appear to be down-faulted (approximately 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 (Knag, 1980; Hellem, 1980; Blomier et al., 2011; Bond et al., 2017) and probably lasted until the early Middle Triassic (Krajewski & Weitschat, 2015; Czarniecka et al., 2020).

Mesozoic basins and platforms

The Svalbard Platform and northern part of the Kong Karls Land Platform are the two main internal Mesozoic structures in the SCTSE. Following cessation of Late Palaeozoic 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 Kong Karls Land Platform is difficult to define. Large, north-east striking Mesozoic syn-and antiforms with Late Mesozoic and Tertiary reverse faults and Lower Cretaceous intrusive or extrusive volcanic rocks characterise 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 Kimmerdgian 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 & Andersen (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-oriented syncline, which covers an area of c. 5000 km^2 in southern and central Spitsbergen. Its margins were initially bounded by a series of N–S-oriented 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 & 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., 2021). During the contraction in Eocene, the WSFTB continued to rise, and flexural loading along the western basin margin thus assisted in maintaining the asymmetric basin shape, being deepest in the west and shallowing significantly eastward (Helland-Hansen & 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).

Probably the CTB 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 most likely continued far beyond its present-day extent.

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

7. Sedimentary basin fill

Total thickness

The thickness of the Carboniferous to Permian successions (TSE 1 – TSE 4; Fig. 4) varies from 380 m to 1800 m, whereas the Mesozoic successions (TSE 5 – TSE 6; Fig 4) vary from 1480m to 2370m, thus summing up to 1860 m 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 m 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-Palaeogene strata, particularly in western Spitsbergen (Braathen et al., 1999).

None of the nearby seismic lines that were available for this study have been depth converted due to uncertain interval velocities, which may cause large uncertainties during attempts to estimate thicknesses.

Lithostratigraphy and depositional systems

TSE 1: The Tournaisian to Visean Billefjorden Group.

The continental sediments of the Billefjorden Group mark the onset of the Mississippian deposition in the SCTSE. The basal surface is a first- order sequence boundary (c.f. Embry, 2009), recording large-scale tectonic reorganisation. 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 accumulation of fine-grained flood plain deposits assigned to the Tournaisian Orustdalen Formation. Lopes et al., (2018) suggest a late Tournaisian to late Visean hiatus in the Hørbybreen Formation. It coincides with a shift in depositional environments from a coarse-grained sand and gravel-dominated braid plain to a fine-grained, vegetated flood plain dissected by meandering rivers (e.g., Steel & Gjelberg, 1981). In the Billefjorden Trough, coarse grained braided stream deposits are locally overlain by heterolithic and coal-bearing floodplain fines. This formation thickens northward along the Billefjorden Fault Zone and pinches out towards the underlying basement in the east. The gradual transition from deposits consistent with wetlands into flood plain red beds with calcrete in the Serpukhovian to Bashkirian Hultberget Formation records a change from humid to semi-arid or arid tropical climate.

TSE 2: The Serpukhovian to Moscovian; lower Gipsdalen Group.

Deposition of the lower Gipsdalen Group (Serpukhovian-Moscovian) took place in a series of narrow, N-S 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 symmetric basin (Johannessen & 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). Cyclicity 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 & Stemmerik, 2015; Smyrak-Sikora et al., 2019; 2021).

TSE 3: The upper Moscovian to 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 & 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 & 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.

TSE 4. The upper Lower to Upper Permian Tempelfjorden Group.

Deposits of the Gipshuken Formation reflects 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 uplift such as the of prominent highs such as Nordfjorden High and the Sørkapp- Hornsund High and (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., 2016; Uchman et al., 2016). Sandstone wedges in the southern part of Spitsbergen are banked to Sørkapp- Hornsund High (Knag 1980) and consistent with an active syn rift basin fill. Regional subsidence in combination with eustatic sea-level rise resulted in deepening of the SCTSE. In addition, continued northward continental drift promoted a climatic cooling, in concert with a globally high silica production in the oceans.

TSE 5: The Triassic to 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 to Middle Triassic Vardebukta, Tvillingodden and Bravaisberget

Formations, outcrop 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 eastward into offshore mudstones of the Lower Triassic Vikinghøgda and the overlying Botneheia formations (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 east-southeast, recording the distal part of a north-westward prograding deltaic clinoform system approaching from the Uralian mountains and the north-eastern part of the Baltic Shield (Smelror et al., 2009; Riis et al., 2008; Glørstad-Clark et al., 2011; Høy & Lundschien, 2011; Klausen et al., 2014; 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; Lundschien 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; Lord et al., 2017; Vigran et al., 2014).The prodeltaic part of this delta system is represented by the Tschermakfjellet Formation (Ladinian/early Carnian), whereas the overlying De Geerdalen Formation (Carnian to early Norian) represent delta slope to delta front and delta plain depositional environment (Fig. 4) (Klausen and Mørk 2013; Lord et al., 2014;2017; Rød et al., 2014). On Edgeøya, fluvial, tidal and delta front deposits are documented in the De Geerdalen Formation, with thick sandstone intervals featuring a lobate geometry found in many parts of the strata (Rød et al., 2014). Infill of small delta front growth basins are particularly evident at Edgeøya (Edwards, 1976; Rød et al., 2014; Smyrak-Sikora et al., 2020; Anell 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 consist of heterolithic intercalated beds of shale, siltstone and sandstone. Red beds with immature to dm thick mature calcrete soil profiles (i.e., hard pans) interbedded with and 1 to 2m 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 colouration (Lord et al., in press). These facies indicate that the Isfjorden Member represent delta top environment. These more condensed succession and prevalent localised subaerial exposure surfaces at the top of the De Geerdalen Formation are consistent with proposed reduction in subsidence at the transition to the Norian and Early Jurassic (c.f. Ryseth et al. 2014). On Hopen to the south-east of the SCTSE the Hopen Member represents a shallow marine interval and can be traced east of Svalbard (Lundschien et al., 2014; Lord et al., in press). This likely indicates early onset of basin sag and 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., in press; Lord et al., in press).

The basal boundary of the lower Norian to lower Bathonian Wilhelmøya Subgroup represents a regional unconformity surface which is overlain by the conglomeratic Slottet Bed that was deposited during a pan Arctic Norian flooding event (c.f. 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 regional change in provenance area and 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 a 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 to Pliensbachian paralic Svenskøya Formation comprises an almost 200 m thick succession in Kong Karls Land, it forms a 5 to 20 m thick condensed, shallow marine succession with numerous hiatuses in central and western Spitsbergen (Olaussen et al., 2018; Rismyhr et al., 2019). Similar thickness trends and hiatuses occur in the SWBS (e.g., Müller et al., 2019). Both trends are linked to the evolving nappes from the Novaya Zemlya Fold and Thrust Belt and migration of the forebulge (Klausen et al. in press). By the Toarcian the variation in thickness is mostly levelled out throughout the archipelago. The upper part of the Wilhelmøya Subgroup is represented by the widespread Toarcian to Bathonian Kongsøya Formation. The formation is highly condensed and dominated by shoreface deposits, commonly separated by offshore sandstones and shales. The uppermost unit of the Kongsøya Formation i.e. top of the Wilhelmøya Subgroup is the Bathonian Brentskardhaugen Bed (Fig. 4). It represents a regional transgression and is composed of a polymictic phosphatic conglomerate containing reworked Toarcian to ?Bajocian fossils (Bäckström & Nagy, 1985; Rismyhr et al., 2019).

TSE 6: The Middle Jurassic to Lower Cretaceous Adventdalen Group.

During deposition of the siliciclastic shelf sediments of the Middle Jurassic to Lower Cretaceous Adventdalen Group, influence of the Uralian as in Triassic and later Novaya Zemlya become now insignificant. Instead, the group records other dramatic switches in paleo-drainage and source area related to uplift in the west and northwest 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 sea floor 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 northwest and west of Spitsbergen (Dypvik & Zakharov, 2012; Koevoets et al., 2018). The upper part of the Agardhfjellet Formation (the Slottsmøya Member) has recently emerged as one of the world's richest sources of Jurassic ichthyosaur and plesiosaur fossils (Delsett et al., 2016), with several number of species including a 10-13 m long pliosaurid (Knutsen et al., 2012).

The overlying upper Ryazanian/Valanginian to lower Barremian Rurikfjellet Formation forms a 200 to 300 m thick coarsening- and shallowing-upward succession (Grundvåg et al; 2019; Jelby et al., 2020; Sliwinska 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 to the 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 northwest (Grundvåg et al., 2019). The upper part of the formation consists of shallow marine to deltaic sandstones forming two separate wedges respectively central and southern Spitsbergen, respectively (Dypvik et al., 1991; Jelby et al., 2020; Grundvåg & Olaussen, 2017; Grundvåg et al., 2019).

The overlying up to 120 m thick fluvio-deltaic succession is assigned to the Barremian – lower Aptian Helvetiafjellet Formation (Fig. 4) (Midtkandal & 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 fill 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; Hurum et al., 2016; Grundvåg et al., 2019). The main source area for this fluvio-deltaic system was exhumed terranes north and west of the SCTSE with depocenters on the shelf further to the south and southeast (Gjelberg & Steel, 1995; Midtkandal & Nystuen, 2009; Grundvåg & Olaussen, 2017). A regional provenance switch is, however, 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 to 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 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).

TSE 7: The Paleocene to 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 Pb/U-ages of 61.6, 59.3 and 55.8 Ma, respectively (Charles et al. 2011, Jones et al. 2017, Jochmann et al. 2021). 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. 2019). Geochemical fingerprinting suggests the Kapp Washington volcanic rocks in North Greenland as source for the oldest bentonite bed, while the younger beds likely represent volcanism in the Nares Strait, Arctic Canada (Jones et al., 2017, Jones et al., 2016). 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 represent the most important coal-bearing unit in Svalbard (Nøttvedt, 1985; Lüthje et al., 2020).

The Eocene basin fill accumulated in a foreland basin which formed in response to the development of the WSFTB. It represents an overall regressive mega-sequence comprising several hundred meters 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 & Grundvåg, 2020). The Paleocene succession was largely sourced from the east, whereas the overlying Eocene to possible 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 & Steel, 2003; Petersen et al., 2016).

Paleogene outliers also occur in several smaller structurally confined basins within the WSFTB (e.g., Blinova et al., 2009; Smelror & Larssen, 2016; Jochmann et al., 2020; Schaaf et al., 2021).

8. Magmatism

Carboniferous.

A steeply dipping or vertical northeast-southeast striking monchiquite (lamprophyre) dyke occurs at Krosspynten in Widjefjorden, Spitsbergen. It is approximately 1.5 m wide and clearly crosscuts 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'schikov, (1964) obtained a K–Ar age of 309 ± 5 Ma for the dyke. However, an ongoing study, applying the 40Ar/39Ar step heating method, indicates an older, possible late Mississippian age for the intrusion (Morgan Ganerød pers. com. 2019).

Early Cretaceous

In Svalbard, Early Cretaceous mafic rocks related to the HALIP are assigned to the Diabasodden Suite (Dallmann, 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 & Rasmussen, 1997, Olaussen 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 ca. 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 occur in fluvial channel deposits within the unit (Olaussen et al., 2018). Ongoing studies using $^{40}Ar/^{39}Ar$ step heating method gave a maximum age of a lava flow of 126.1 +- 1.7 Ma (Morgan Ganerød, pers. com. 2020).

9. Heat flow and pressure regimes

The current geothermal gradient and heat flow vary from 25 to 55°C/km and 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 in the Eocene to 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).

Localised Neogene to Quaternary volcanism reported in north-western 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.

Due to the out-out-equilibrium conditions the pore-pressure regimes are also diverse throughout Svalbard, ranging from stratigraphic units experiencing severe under-pressure to those experiencing mild over-pressure. While the more subtle abnormal pressures can be explained by topography driven flow, the more severe cases of under pressure cannot. The most reliable quantitative pressure data are derived from the Longyearbyen CO_2 Lab boreholes in Adventdalen (Braathen et al., 2012; Olaussen et al., 2019) where long-term pressures were recorded (Birchall et al., 2020). Parts of the Mesozoic succession are severely under-pressured, with pressures up to 60 bar below hydrostatic recorded in some low permeability (< 2 mD) reservoir units and in the lower parts of the regional cap rock unit, the Agardhfjellet Formation (Fig. 4) (Birchall et al., 2020). Because the reservoir intervals are extensively outcropping some 15 km north of the drill site, and there is no evidence of a major lateral seal, the underpressure must have developed recently (i.e., in the late Neogene) and be in a present state of disequilibrium. Numerical modelling also supports this, with the most likely candidate for the cause of underpressure being as a response to late Neogene glacial loading, unloading and erosion (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).

10. Petroleum geology

Discovered and hydrocarbon 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).

The consequences of Pliocene-Pleistocene uplift and erosion in the SCTSE are numerous: firstly it may have shut down hydrocarbon expulsion from source rocks or changed migration routes from potential kitchen areas. Secondly, the erosion of cap rocks, trap tilting likely led to previously filled

traps to spill. Thirdly, the reduction of overburden and changes in stress would have altered the geomechanical properties of cap rocks, reservoirs, and faults. Finally, the changes in PVT conditions, in addition to influencing migration, would have enabled the exsolution and expansion of gas from oil accumulations. Consequently, oil from previously adequate traps in the SCTSE may then have spilled to structures at shallower depths and eventually leaked to the surface. Indeed, it is very likely this process is still ongoing today.

Hydrocarbon systems

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 to Longyearbyen, possibly representing a local energy source for the future (Ohm et al., 2019). Bituminous stained sandstones and carbonates occurring at several stratigraphic levels of the SCTSE, indicate the presence of multiple source rocks and migration phases that record secondary oil migration and dis-migration into previously efficient traps (Fig. 4). Paleo-hydrocarbon 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 have 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 palaeo-hydrocarbon 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) document ongoing near-shore gas seepage in northern Isfjorden, while Hodson et al (2020) illustrate 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.

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, 3) groups are proven potential source rock units in Central Spitsbergen (Koeverden et al., 2010.; Nicolaisen et al., 2019). A normal distribution of T_{max} of 440 °C suggesting maturation in the late oil window (Nicolaisen et al., 2019). Coaly mudstones and organic rich flood plain deposits to lacustrine mudstone in the Mississippian Billefjorden Group in central Spitsbergen have reported TOC values of 11-28 wt.%, and HI of c. 160-350 mg HC/g 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 & Karlsen, 2011).

Organic-rich marine calcareous mudstone in the Gipsdalen Group occur as either thin beds intersecting carbonates or evaporites or as thicker (up to 10 m) unit of fusulinid rich shaly limestone; the Lower Permian Brucebyen Bed (Nicolaisen et al., 2019). The thin inter-beds have an average TOC of 1-10 wt.% and HI values of 200-400 mg HC/g TOC. The beds seldom reach thickness above 30-40 cm but might sum 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 mg HC/g TOC (Nicolaisen et al., 2019), thus forming the most significant source rock in the Gipsdalen Group.

Mesozoic (TSE 5- TSE6)

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 to Lower Cretaceous Agardhfjellet Formation (TSE 6). Their offshore near time-equivalent counterparts: the Steinkobbe and Hekkingen Formations, respectively, are known to charge both numerous fields in the Norwegian Barents Sea (Henriksen et al., 2011a; Leith et al., 1993; Ohm et al., 2008; Abay et al., 2018). Both the Botneheia and Agardhfjellet formations were deposited in relatively shallow shelf waters, periodically under anoxic sea floor conditions, in distal pro-deltaic settings in front of large, prograding delta systems (Glørstad-Clark et al., 2011; Anell et al., 2014a, b; 2016; Koevoets et al., 2018; Wesenlund et al., 2022). Bitumen in Mesozoic sandstones from outcrops and cored boreholes indicate that both OMM units have once been active source rocks (Abay et al., 2017) The maturation of the Mesozoic OMM within the SCTSE records a west-east trend from burned out/over mature in the southwest 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 diageneses 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; Olaussen et al., 2018).

The Botneheia Formation is from 80 to 160 m thick, and contains dominantly kerogen type II in its upper part and type III in its lower part, with TOC values ranging from c. 1–11 wt. % with the Blanknuten Member in the upper part of the formation exhibiting the highest organic content (Mørk & Bjorøy, 1984; Krajewski, 2013; Wesenlund et al., 2021; 2022). On northwest 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 median TOC value of 8.10 ± 1.06 wt% and HI = 538 ± 42 mg HC/g (Wesenlund et al., 2021). This upper member is also typically rich in phosphate, suggesting 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) suggests 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 versus aromatic hydrocarbons compared to the oil-prone, phosphate-bearing upper part of the unit.

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

The Agardhfjellet Formation; this up to 240 m thick Bathonian to Ryazanian organic rich mudstone dominated formation contains more than 100 m thick (accumulative) of OMM with TOC contents ranging 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, shows that the formation contains a mixture of type II and type III kerogen and TOC of 6 to 10 %, a HI 50 to 200 mg HC/ g TOC. Tmax varies from 455 to 275 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, preserved part is immature with reported TOC values of up to 40 % with a Tmax 410 and %VR of variation from 0.38 to 0.42 (Olaussen et al., 2018).

Another regionally extensive organic-rich mudstone unit with some source potential occur in the basal part of the lower Aptian to 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 mg HC/g TOC (Grundvåg et al., 2019). An Aptian source rock unit is proven in the SWBS, but here as 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 diagram shows plot between II and III kerogen) and HI ranging between 151 and 410 mg HC/g 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 bitumen yield of up to 320 mg/g TOC (Marshall et al., 2015). The bitumen has thus migrated, enriching the upper parts of the investigated coal seams and partly the immediate overlying sandstone (Marshall et al., 2015). The coals represent thick accumulations of marine influenced, peat deposits, and have a better source rock potential and oil-generating properties than the closely associated organic-rich flood plain deposits. The coal bearing strata have locally significant amounts of gas, which regularly was encountered as a hazard during coal 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 partly permeability trend of the Upper Palaeozoic 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; Olaussen et al., 2018; Haile et al., 2018). Upper Carboniferous to 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 & Worsley, 1995; Ehrenberg et al., 2001; Blomeier et al., 2009, Sorento et al., 2019). Triassic sandstones (TSE 4) in the east potentially exhibit moderate porosities (12 to 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/fluvial to lacustrine and paralic sandstone units of the Billefjorden Group. The sandstone to 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 braid plain deposits overlain by shoreline and delta front sandstone units and alluvial fans banked to the master faults (Johannessen & Steel, 1992, Braathen et al., 2011; Smyrak-Sikora et al., 2018).

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 & Talbot, 2003).

The platform carbonates of the Gipsdalen Group have good visible porosity (Ahlborn & 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 SWBS (Larssen et al., 2002). In the middle part of TSE 3, corresponding to the Gipshuken Formation (Fig. 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 the Lomfjorden area. Petrographic analyses have documented both inter and intra-particle porosity of 15 to 17% in grainstones and intra crystalline porosity of 20% in dolomites. The porous platform units are sheet like and persists 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) 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 seen as partly unconsolidated.

Triassic to Middle Jurassic (TSE 5)

The Lower Triassic Vardebukta Formation in the eastern part of the SCTSE features an upwards coarsening para-sequence that terminates in a series of upper shoreface and to fluvial channel unit that may provide good reservoir properties (Mørk et al., 1982).

The key Triassic reservoir interval occurs in the De Geerdalen Formation. The sandstone to shale net to gross (N/G) of the De Geerdalen (and the age and facies equivalent Snadd Formation offshore) increases significantly to the east and southeast 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 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 to Bathonian condensed paralic sandstone unit, typically less than 20 metres thick, 'tight' sandstone and with numerous hiatuses (Bäckstrøm & Nagy, 1984; Rismyhr et al., 2018) Subsurface Adventdalen). This subgroup has been suggested to be a potential CO_2 storage unit, forming an unconventional reservoir, that relies on a permeable fracture system (Braathen et al., 2012; Senger et al., 2015; Ogata et al., 2012; 2014; Olaussen et al., 2019; Mulrooney et al., 2019).

In the eastern SCTSE (i.e., Kong Karls Land), the Wilhelmøya Subgroup thickens to ca. 200 m. Here, the reservoir sandstones are poorly consolidated occasionally occurring as loose sand and appear to be porous and permeable (Olaussen 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 to 0.3 N/G sandstone shale ratio. The overlying amalgamated 12 – 30m thick channelised Norian/Rhaetian part of the Sjøgrenfjellet Member of the Svenskøya Formation in Kong Karls Land and Hopen respectively has good reservoir potential with an estimated sandstone shale ratio of 0.9 to 1 (Lord et al., 2019). The remaining part of the heterolithic deposits of the Hettangian to lower Pliensbachian Sjøgrenfjellet Member shows a variation of sandstone shale ratio from 0.5 to 0.7.

The 20–50 m thick, upper Pliensbachian upper Toarcian Mohnhøgda Member of the Svenskøya and the upper Toarcian to Aalenian Kongsøya Formation shows a sandstone shale ratio range from 1 in central Spitsbergen to 0.7 to 0.8 in the east. On Kong Karls Land, the overlying Kongsøya Formation shales out to the east on Kong Karls Land, from Svenskøya to Kongsøya at 35km. This also indicates in a prominent paleo-drainage shift towards a more easterly located source.

Middle Jurassic to Lower Cretaceous (TSE 6)

In western Spitsbergen the Kimmeridgian Oppdalsåta Member of the Agardhfjellet Formation comprises four to five 10 - 15m thick shallowing upward sequences with 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 southward into the offshore area of the SCTSE (Grundvåg & Olaussen, 2017). We estimate the sandstone shale ratio of this succession in south to range from c. 0.5 in its lower part to 0.8 in its upper parts.

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 m to more than 150 meters, reflecting deposition within large-scale incised valleys (Gjelberg & Steel, 1995; Midtkandal et al., 2008; Midtkandal & Nystuen, 2009; Olaussen et al., 2018; Grundvåg et al 2019), as well as syn-tectonic movements in the Barremian (Nemec et al., 1988; Onderdonk & Midtkandal, 2010). The lowermost sandstone unit, the Festningen Member, is a regionally extensive 5 to 15 m thick cross-bedded sandstone sheet of braid plain origin. The sandstone shale ratio is generally high, ranging from 0.6 to 0.9.

Despite low porosities of 6 to 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 CO_2 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) which exhibit 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 organised 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 south-eastward prograding shelf-prism clinoform system (Grundvåg et al., 2014a; Helland-Hansen & 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 consists 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 (Table 2; Fig. 4) (Nøttvedt et al. 1993). The sealing capability of potential sealing rocks in the SCTSE is complicated by their laterally heterogenous nature and recent uplift.

The sequence of the Hekkingen and Fuglen formations provides the most important caprock in the Barents Sea (Ohm et al., 2008; Paulsen et al., 2022). In Svalbard, the Agardhfjellet Formation forms a time-equivalent caprock, which is fully cored by four research boreholes of the Longyearbyen CO_2 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., 2018).

The rheological impacts of Cenozoic uplift may be profound in caprock effectiveness. Previous deep burial has left the potential seals mechanically and chemically over-compacted for their present-day depths. This may enhance some mechanical properties, as is evident by extremely high leak-off pressures in the Fuglen Formation offshore (Paulsen et al., 2022), often more that the lithostatic pressure. Conversely it may also make the caprock 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; Betlem et al. 2019; Mulrooney et al., 2018). Particularly permafrost appear to be an efficient shallow seal as evident thermogenic gas 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 likely elsewhere, as demonstrated by numerous active seeps and flares (Abay et al., 2017). The occurrence of a large gas accumulation (and blowout) below permafrost in 600-year-old moraine sediments 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).

Svalbard as a geological playground

Svalbard as a geological playground will remain a benefit to future generations of geoscientists. The excellent and nearly complete stratigraphic sections will amongst others allow geologists to look back in time and scrutinize the climatic changes recorded in Svalbard's geological record.

Due to its strategic location between multiple Arctic terranes, well-established geological framework, plethora of available data, and modern infrastructure offering easy access to World-class outcrops, Svalbard will remain a geological playground and hopefully inspire eager geoscientists also in the future. Hydrocarbons will inevitably continue to be an important component of the future energy mix despite our common efforts in transitioning to renewables. With the current geopolitical situation in mind, Norway's role in suppling energy to the European market seems to become increasingly important. Moreover, as we face the largest challenge of our time, climate change and over-consumption of resources, investigating proxies and processes driving climate change, both past and present, is a paramount task for any 21st century geoscientist. As such, despite its impaired potential of ever becoming a petroleum province, Svalbard with its excellent exposures and nearly stratigraphically complete Carboniferous to Paleogene succession, will be a key asset in future regional resource estimates, prospect de-risking, and integrated endeavours to increase our understanding of the subsurface of the Barents Shelf. More importantly, the many paleo-climatic changes recorded in the sedimentary rock record on Svalbard can aid in ongoing and future research efforts that aim to scrutinize factors causing dramatic and irreversible climate changes. For these reasons, there is no doubt that Svalbard will continue to be an important training ground for the next generation of geoscientists and explorationists alike.

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Figure Captions

Figure 1. Structural framework of the Svalbard Composite Tectono-Stratigraphic Element. Only the area within the black line in A and stippled line in B is discussed in this paper. B: Geological map of Svalbard excluding Bjørnøya. LYB: Longyearbyen, BAB Barentsburg, NYÅ: Ny Ålesund, SVE: Svea, PYM Pyramiden, AB: Agardhbukta, KV: Kvalvågen. Geological maps from Dallman (2015). Figure 2. Principal data sets. 2D conventional seismic lines as grey coloured lines. Hydrocarbon exploration wells are marked with numbers 7nnn/n-n and follows annotation as recommended by the Norwegiam Petroleun Directoratet.

Figure 2. Principal data sets. A: 2D conventional seismic lines as grey coloured lines. Hydrocarbon exploration wells are marked with numbers 7nnn/n-n and follows annotation as recommended by the Norwegian Petroleum Directorate (NPD). Others are coal drilling or R&D wells. Red line at 7819/12-1 is location of seismic cross section in fig. 8. Green scratched areas are national parks while red is national reserves.

Figure 3. Composite seismic lines crossing central Spitsbergen from west to east, continuing offshore in a southward direction to the Garderbanken High south of the SCTSE. Location of lines X X' are seen in figure 1A and Y Y' in 1B. TD: Total Depth; Pr.: Well projected.

Figure 4. Composite summary of chrono-/lithostratigraphy, tectonic events and petroleum systems (i.e. previous petroleum systems) of the tectonic stratigraphic sequences (TSE 1 to TSE 6) documented in this study. Geologic Time Scale after Gradstein, Ogg et al. (. 2020; https://timescalefoundation.org.). The column is based on the most recent stratigraphic work available, including those of Vigran et al., (2014), Paterson et al., (2016), Koevoets et al., (2018), Smelror et al., (2018), Jochmann et al., (2020), and Sliwinska et al., (2020). Abbreviations of lithostratigraphic units and structural elements (from top down): FG: Forlandsundet Graben; CTB: Central Tertiary Basin; As: Aspelintoppen Formation; Ba: Battfjellet Formation; FR: Frysjaodden Formation; Gr: Grumantbyen Formation; Ba Basilika Formation; Fi: Firkanten Formation; KKL lava flows: Kong Karls Land lava flows; Ca: Carolinefjellet Formation; He: Helvetiafjellet Formation; Ru: Rurikfjellet Formation; Mb: Myklegardfjellet Bed; Ag; Agardhfjellet Formation; BB: Brentskardhaugen Bed; Ko: Kongsøya Formation; Sv: Svenskøya Formation; Fl: Flatsalen Formation; SB: Slottet Bed; DeG: De Geerdalen Formation; Ts: Tschermakfjellet Formation; Br: Bravaisberget Formation; Bo: Botneheia Formation; Tv: Tvillingodden Formation; Va: Vardebukta Formation; Vi Vikinghøgda Formation; Ks: Kapp Starostin Formation; Vø: Vøringen Member; Gi: Gipshuken Formation; Wo:

Wordiekammen Formation; Mi: Minkenfjellet Formation; Eb: Ebbadalen Formation; Hu: Hultberget. Mu: Mumien Formation; Hø: Hørbybreen Formation.

Figure 5. Cross sections from Spitsbergen A: Cross section from central to eastern Spitsbergen. Modified from Dallmann 2015 and Smyrak- Sikora et al., 2019. Lomfjorden Fault Zone from Haremo & Andersen 1992. Location of cross sections are seen in Fig. 1B: Cross section from West Spitsbergen Fold and Thrust Belt; simplified and modified after Braathen et al., (1995) and for details of the cross section. The estimated depth of the cross section is based on poor-resolution offshore seismic data (Bergh et al. 1997), and a crude velocity model.

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

Figure 7. Temperature gradients from exploration and research wells

Figure 8. The only example of a drilled prospect based on subsurface mapping in Svalbard, Reindalspasset, Well 7816/11-1. The target was a play with Pennsylvanian rotated fault block as trap and sandstone and carbonates as reservoir which were sourced from Mississippian coal and shales. Apart from the age of the strata it is the most successful play type on the Norwegian Continental Shelf i.e., a structural unconformity trap. TD: Terminal Depth; BCU: Base Cretaceous Unconformity, i.e., Base Rurikfjellet Formation. Colour legend of 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 Fig, 4 for stratigraphy

Figure 9. Maturation trend of Mesozoic organic rich marine mudstone (OMM) based on available vitrinite, Tmax, geochemistry data of bitumen (Mørk & Bjorøy, 1984; Abay et al., 2017; Ohm et al., 2019), and diagenesis of sandstones (Mørk, 2013; Haile et al., 2017; 2021) and mostly based on degree of quartz cementation (c.f., Walderhaug, 1996; Bjørlykke & Jahren, 2015).

Table Captions

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

Nr.	NPD well ID Borehole name	Easting Northing	Longitude Latitude	Spudded Completed	Operating company	Elevation KB (m) Total depth (m MD)	Youngest age Youngest formation	Oldest age Oldest formation	Likely reservoir target Tectono-stratigraphic element (TSE)	Likely reason for drilling and other comments
0	- Kvadehuken I	422970 8766727	11°23'23" 78°57'03"	summer 1961 16.06.1963	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* Grønnfjorden I	484198 8654805	14°20'36" 77°57'34"	09.06.1963 12.08.1967	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"	01.08.1965 15.03.1966	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"	23.08.1967 10.08.1981	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"	11.08.1971 29.09.1971	Fina	9,1 908	Late Triassic De Geerdalen Fm	Middle Triassic Botneheia Fm	? TSE 4	Surface mapping.
5	*7722/3-1* Raddedalen	678904 8660316	22°41'50" 77°54'10"	02.04.1972 12.07.1972	CFP	84 2823	Late Permian Kapp Starostin Fm	Ordovician Horbyebreen Fm	? TSE 1, TSE 3	Surface mapping. Regional geophysical data.
6	*7721/6-1* Plurdalen	659992 8638282	21°50'00" 77°44'33"	29.06.1972 12.10.1972	Fina	144,6 2351	Middle Triassic Botneheia Fm	Pre-Devonian ?	? TSE 0, TSE 1, TSE 3	Surface mapping. Regional geophysical data.
7	*7811/2-1* Kvadehuken II	422970 8766727	11°23'23" 78°57'03"	01.09.1972 19.06.1973	NPN	0 479	Early Permian Gipshuken Fm	Pre-Devonian Hecla Hoek	? TSE 0, TSE 3	Surface mapping.
8	*7625/5-1* Hopen II*	767641 8535807	25°28'00" 76°41'15"	20.06.1973 20.10.1973	Fina	314,7 2840	Late Triassic-Middle Jurassic Wilhelmøya Subgroup	Middle Carboniferous Ebbadalen Fm	Numerous potential reservoirs TSE 2, TSE 3, TSE 4	Some limited offset 2D seismic offshore Hopen. Otherwise surface mapping.
9	*7811/2-2* Kvadehuken III	424853 8764140	11°33'11" 78°55'32"	13.08.1973 16.06.1974	NPN	0 394	Early Permian Gipshuken Fm	? ?	? TSE 0, TSE 3	Surface mapping.
10	*7811/5-1* Sarstangen	422845 8741814	11°28'40" 78°43'36"	15.08.1974 01.12.1974	NPN	5 1113	Oligocene Sarstangen conglomerate	Pre-Devonian Hecla Hoek	? TSE 6	Surface mapping. Easy access to drill site
11	*7815/10-1* Colesbukta*	500325 8671916	15°02'00" 78°07'00"	13.11.1974 01.12.1975	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* Tromsøbreen I	552582 8533670	17°05'30" 76°52'31"	11.09.1976 19.09.1977	NPN	6,7 990	Early Cretaceous Carolinefjellet Fm	Late Triassic-Middle Jurassic Wilhelmøya Subgroup	Wilhelmøya Subgroup TSE 4	Surface mapping.
13	*7715/1-1* Vassdalen II*	503990 8639407	15°11'15" 77°49'57"	10.01.1985 14.07.1987	TA	15,13 2481	Eocene Frysjaodden Fm	Carboniferous (?) Billefjorden Gp (?)	Numerous potential reservoirs TSE 1 (?), TSE 3, TSE 4	Surface mapping.
14	*7617/1-2* Tromsøbreen II*	552650 8533700	17°05'38" 76°52'31"	20.07.1987 24.08.1988	T-PG	6,7 2337	Early Cretaceous Carolinefjellet Fm	Early Permian Gipshuken Fm	Numerous potential reservoirs TSE 2, TSE 3, TSE 4	Surface mapping.
15	*7715/1-2* Vassdalen III*	503990 8639407	15°11'15" 77°49'57"	28.02.1988 01.09.1989	TA	15,13 2352	Eocene Frysjaodden Fm	Middle Triassic Botneheia Fm	Numerous potential reservoirs TSE 3, TSE 4	Surface mapping.
16	*7816/12-1* Reindalspasset I*	544775 8665611	16°56'31" 78°03'28"	17.01.1991 11.04.1991	NH/SNSK	182,5 2315	Early Cretaceous Carolinefjellet Fm	Middle Carboniferous Hultberget Fm	Numerous potential reservoirs TSE 1, TSE 3, TSE 4	Sparse 2D seismic acquisition prior to drilling. Comprehensive surface mapping.
17	*7814/12-1* Kapp Laila I*	493560 8671260	14°53'38" 78°06'52"	22.02.1994 08.05.1994	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 withreported liquid hydrocarbons
‡wells that tested gas in producible quantities

Table 1

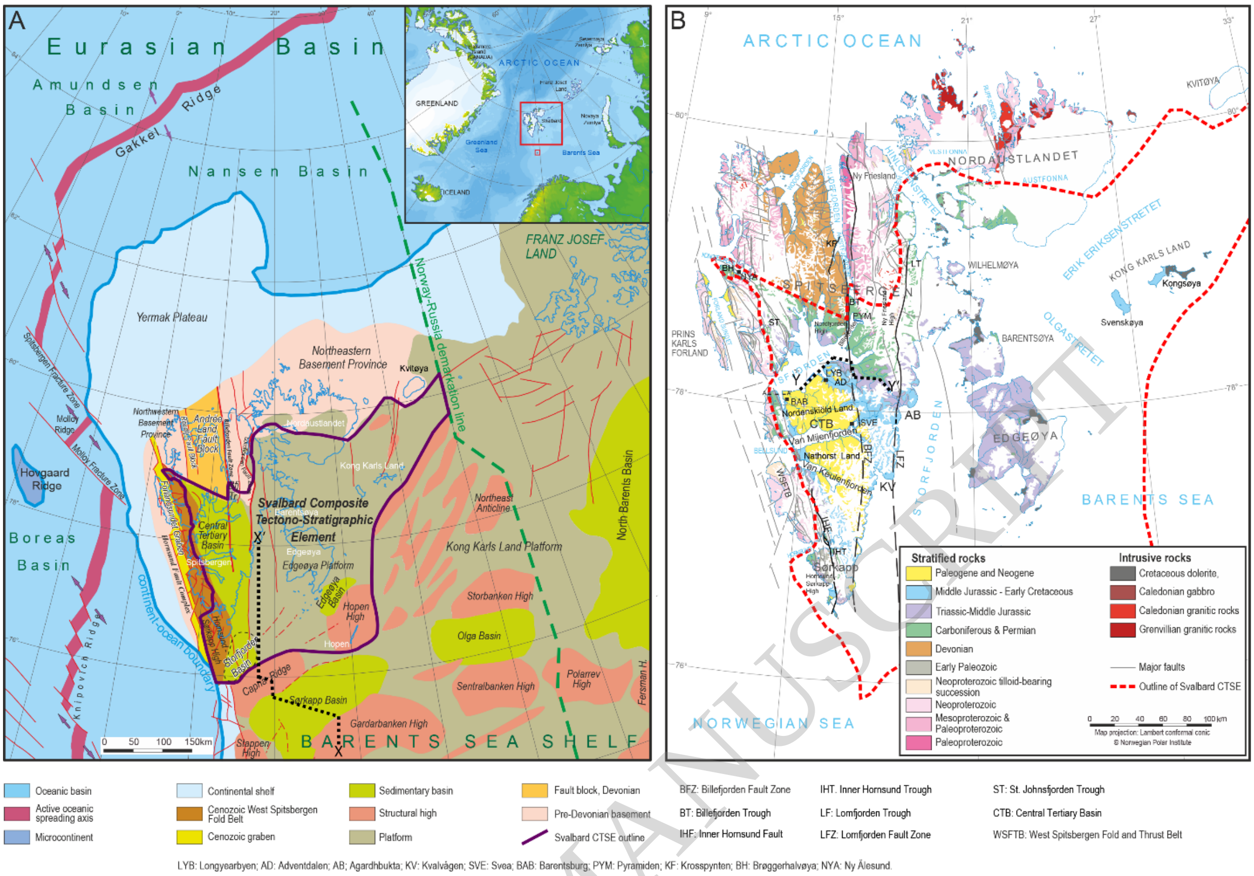

A
Eurasian Basin
Amundsen Basin
Gakkel Ridge
Nansen Basin
ARCTIC OCEAN
GREENLAND
FRANZ JOSEF LAND
Yermak Plateau
Northeastern Basement Province
Kvitøya
Norway-Russia demarcation line
Hovgaard Ridge
Boreas Basin
Svalbard Composite Tectono-Stratigraphic Element
Central Tertiary Basin
Edgeøya Platform
Kong Karls Land Platform
Northeast Anticline
Storbanken High
Olga Basin
Hopen High
North Barents Basin
Sentralbanken High
Polarrev High
Sørkapp Basin
Gardarbanken High
Stappen High
Fersman H.
Knipovich Ridge
continent-ocean boundary
BARENTS SEA SHELF
B
ARCTIC OCEAN
NORDAUSTLANDET
SPITSBERGEN
KVITØYA
WILHELMØYA
KONG KARLS LAND
ERIK ERIKSENSTRETET
Kongsøya
Svenskøya
BARENTSØYA
OLGASTRETET
EDGEØYA
BARENTS SEA
PRINS KARLS FORLAND
NORWEGIAN SEA
STORFJORDEN
CTB
AB
KV
Sørkapp
Stratified rocks
Paleogene and Neogene
Middle Jurassic - Early Cretaceous
Triassic-Middle Jurassic
Carboniferous & Permian
Devonian
Early Paleozoic
Neoproterozoic tilloid-bearing succession
Neoproterozoic
Mesoproterozoic & Paleoproterozoic
Paleoproterozoic
Intrusive rocks
Cretaceous dolerite
Caledonian gabbro
Caledonian granitic rocks
Grenvillian granitic rocks
Major faults
Outline of Svalbard CTSE
Oceanic basin
Active oceanic spreading axis
Microcontinent
Continental shelf
Cenozoic West Spitsbergen Fold Belt
Cenozoic graben
Sedimentary basin
Structural high
Platform
Fault block, Devonian
Pre-Devonian basement
Svalbard CTSE outline
BFZ: Billefjorden Fault Zone
BT: Billefjorden Trough
IHF: Inner Hornsund Fault
IHT: Inner Hornsund Trough
LF: Lomfjorden Trough
LFZ: Lomfjorden Fault Zone
ST: St. Johnsfjorden Trough
CTB: Central Tertiary Basin
WSFTB: West Spitsbergen Fold and Thrust Belt
LYB: Longyearbyen; AD: Adventdalen; AB; Agardhbukta; KV: Kvalvågen; SVE: Svea; BAB: Barentsburg; PYM: Pyramiden; KF: Krosspynten; BH: Brøggerhalvøya; NYA: Ny Ålesund.

Figure 1

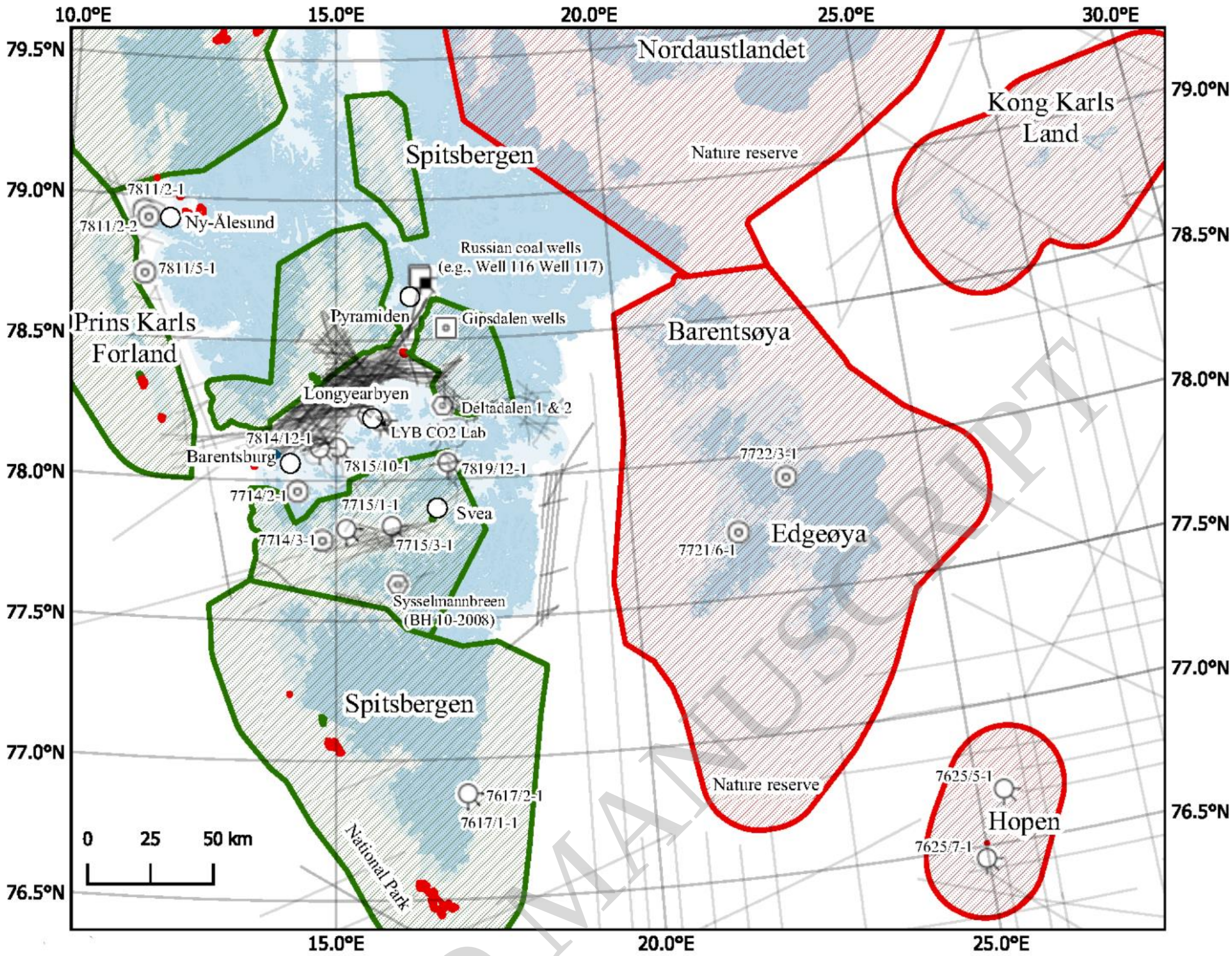
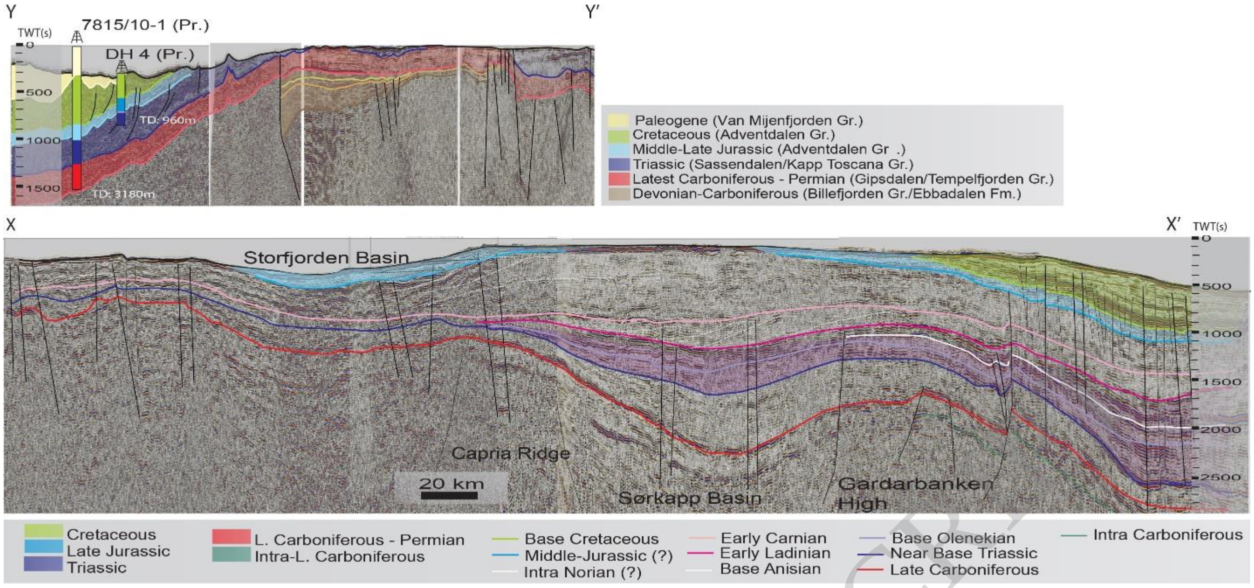

10.0°E
15.0°E
20.0°E
25.0°E
30.0°E
79.5°N
79.0°N
78.5°N
78.0°N
77.5°N
77.0°N
76.5°N
Nordaustlandet
Kong Karls Land
Spitsbergen
Nature reserve
7811/2-1
7811/2-2
Ny-Ålesund
7811/5-1
Russian coal wells (e.g., Well 116 Well 117)
Prins Karls Forland
Pyramiden
Gipsdalen wells
Barentsøya
Longyearbyen
Deltadalen 1 & 2
LYB CO2 Lab
7814/12-1
Barentsburg
7815/10-1
7819/12-1
7722/3-1
7714/2-1
7715/1-1
Svea
7714/3-1
7715/3-1
7721/6-1
Edgeøya
Sysselmannbreen (BH 10-2008)
Spitsbergen
Nature reserve
7625/5-1
7617/2-1
7617/1-1
Hopen
7625/7-1
0 25 50 km
National Park
15.0°E
20.0°E
25.0°E

Figure 2



Y
Y'
TWT(s)
7815/10-1 (Pr.)
DH 4 (Pr.)
TD: 960m
TD: 3180m
Paleogene (Van Mijenfjorden Gr.)
Cretaceous (Adventdalen Gr.)
Middle-Late Jurassic (Adventdalen Gr .)
Triassic (Sassendalen/Kapp Toscana Gr.)
Latest Carboniferous - Permian (Gipsdalen/Tempelfjorden Gr.)
Devonian-Carboniferous (Billefjorden Gr./Ebbadalen Fm.)
X
X'
Storfjorden Basin
Capria Ridge
20 km
Sørkapp Basin
Gardarbanken High
Cretaceous
Late Jurassic
Triassic
L. Carboniferous - Permian
Intra-L. Carboniferous
Base Cretaceous
Middle-Jurassic (?)
Intra Norian (?)
Early Carnian
Early Ladinian
Base Anisian
Base Olenekian
Near Base Triassic
Late Carboniferous
Intra Carboniferous

Figure 3

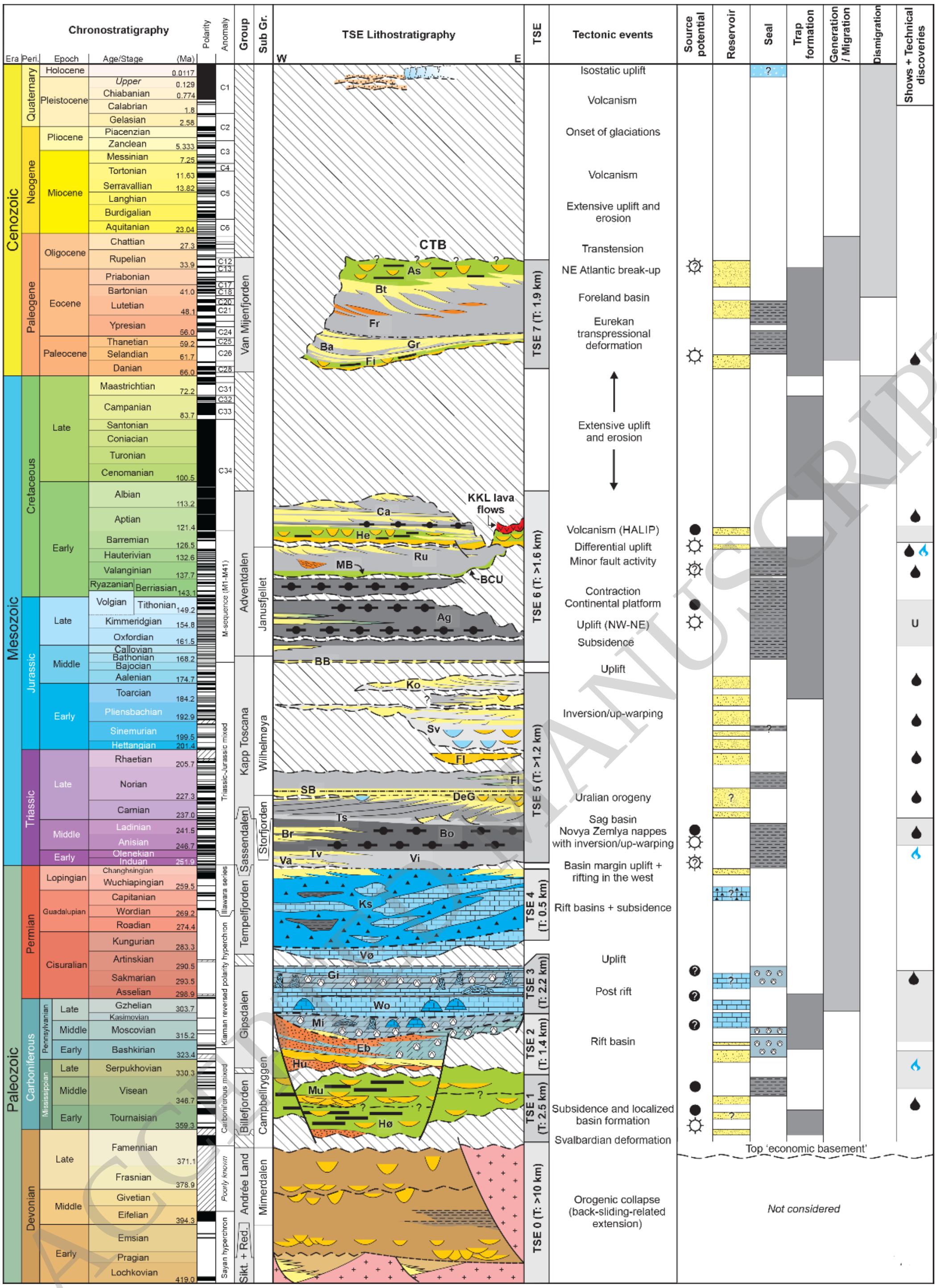

Chronostratigraphy
TSE Lithostratigraphy
TSE
Tectonic events
Source potential
Reservoir
Seal
Trap formation
Generation / Migration
Dismigration
Shows + Technical discoveries
Cenozoic
Mesozoic
Paleozoic
Top 'economic basement'
Not considered

Figure 4

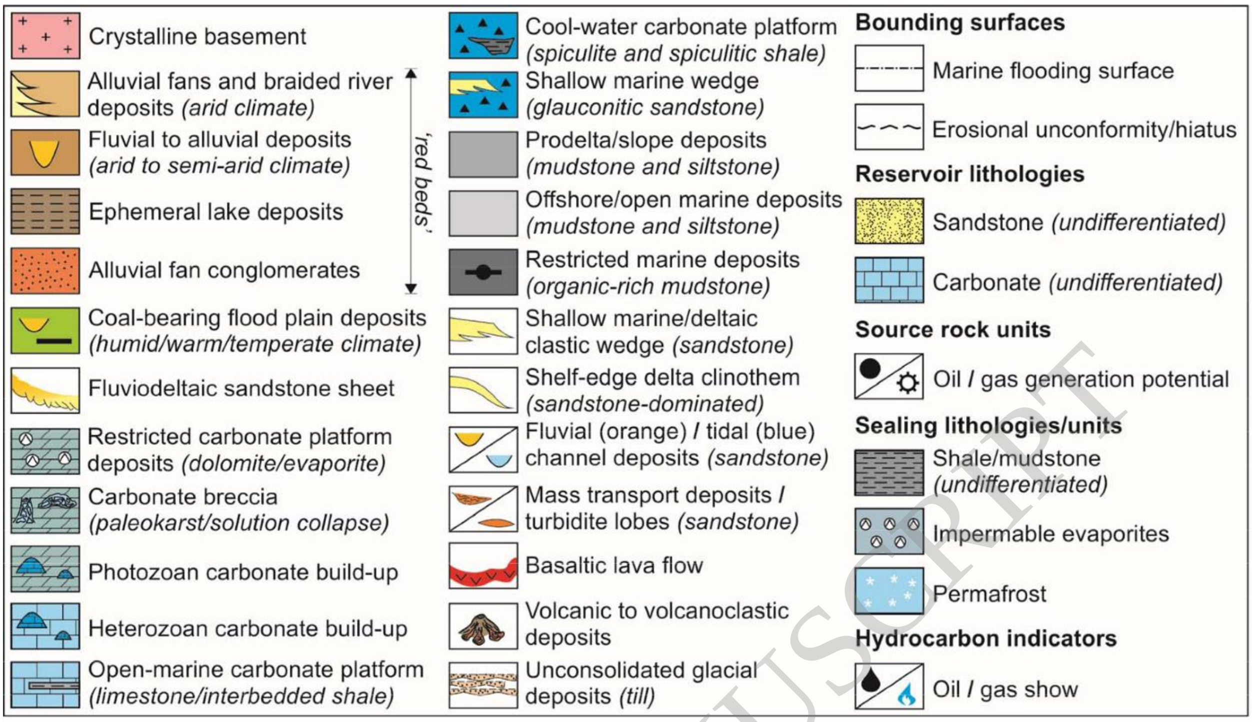


Figure 4(continued)

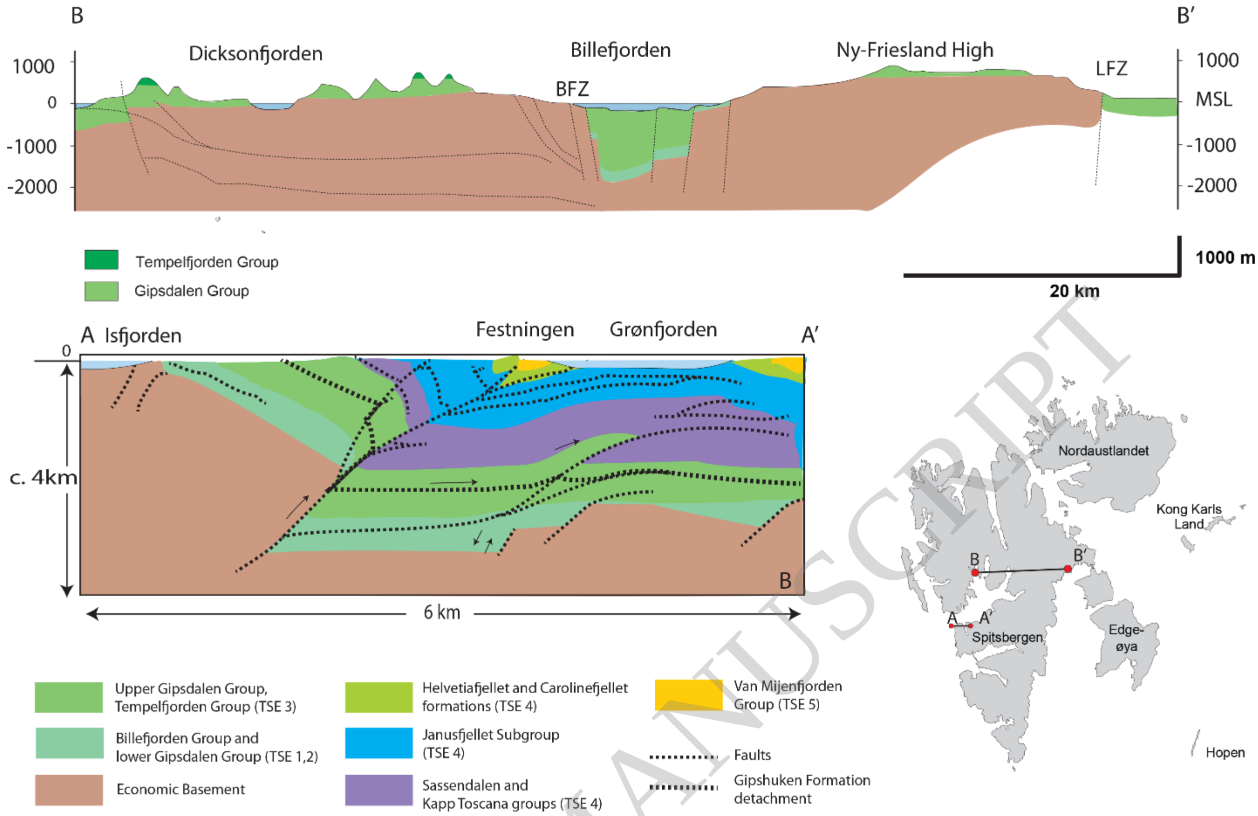
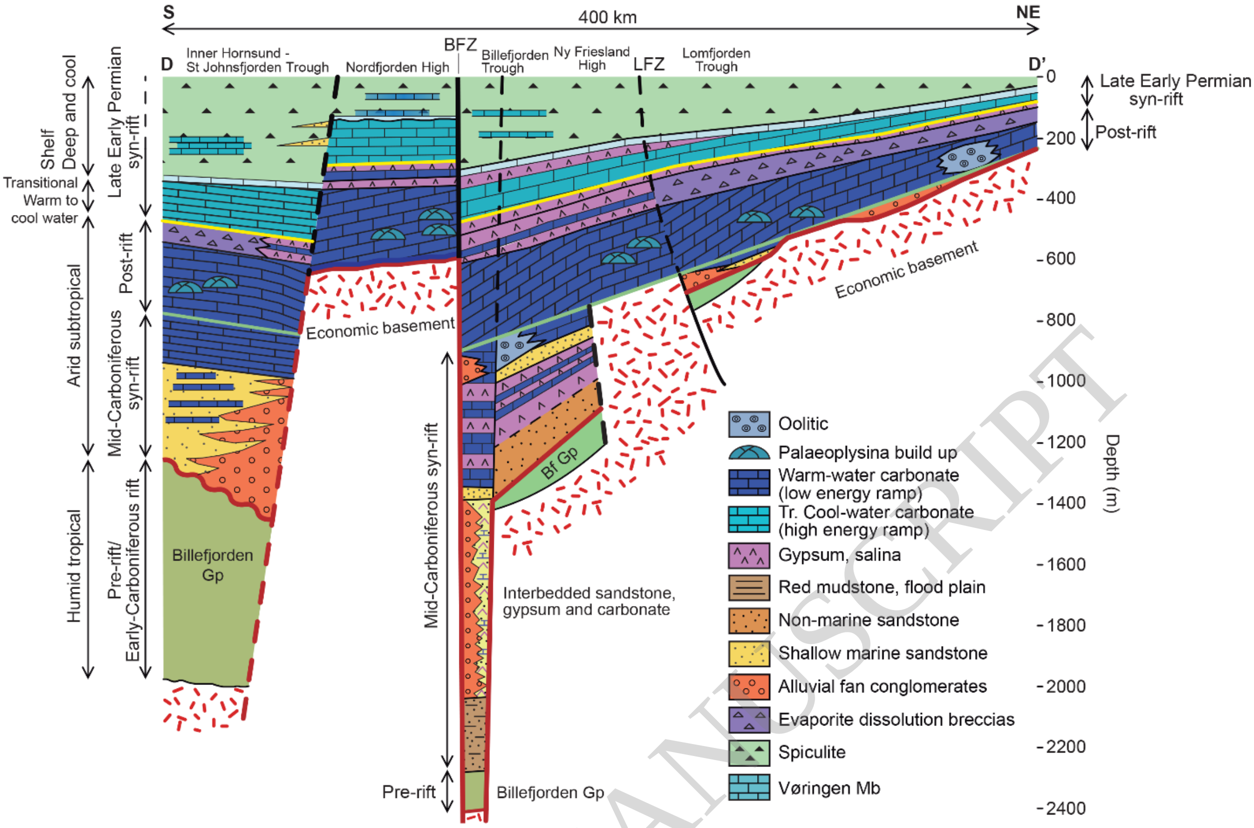

B
B′
Dicksonfjorden
Billefjorden
Ny-Friesland High
BFZ
LFZ
1000
0
-1000
-2000
MSL
Tempelfjorden Group
Gipsdalen Group
1000 m
20 km
A Isfjorden
Festningen
Grønfjorden
A′
c. 4km
6 km
B
Nordaustlandet
Kong Karls Land
Spitsbergen
Edgeøya
Hopen
Upper Gipsdalen Group, Tempelfjorden Group (TSE 3)
Billefjorden Group and lower Gipsdalen Group (TSE 1,2)
Economic Basement
Helvetiafjellet and Carolinefjellet formations (TSE 4)
Janusfjellet Subgroup (TSE 4)
Sassendalen and Kapp Toscana groups (TSE 4)
Van Mijenfjorden Group (TSE 5)
Faults
Gipshuken Formation detachment

Figure 5



S
400 km
NE
D
Inner Hornsund - St Johnsfjorden Trough
Nordfjorden High
BFZ
Billefjorden Trough
Ny Friesland High
LFZ
Lomfjorden Trough
D'
Shelf Deep and cool
Transitional Warm to cool water
Arid subtropical
Humid tropical
Late Early Permian syn-rift
Post-rift
Mid-Carboniferous syn-rift
Pre-rift/ Early-Carboniferous rift
Billefjorden Gp
Economic basement
Mid-Carboniferous syn-rift
Pre-rift
Billefjorden Gp
Bf Gp
Interbedded sandstone, gypsum and carbonate
Economic basement
Late Early Permian syn-rift
Post-rift
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
Depth (m)
Oolitic
Palaeoplysina build up
Warm-water carbonate (low energy ramp)
Tr. Cool-water carbonate (high energy ramp)
Gypsum, salina
Red mudstone, flood plain
Non-marine sandstone
Shallow marine sandstone
Alluvial fan conglomerates
Evaporite dissolution breccias
Spiculite
Vøringen Mb

Figure 6

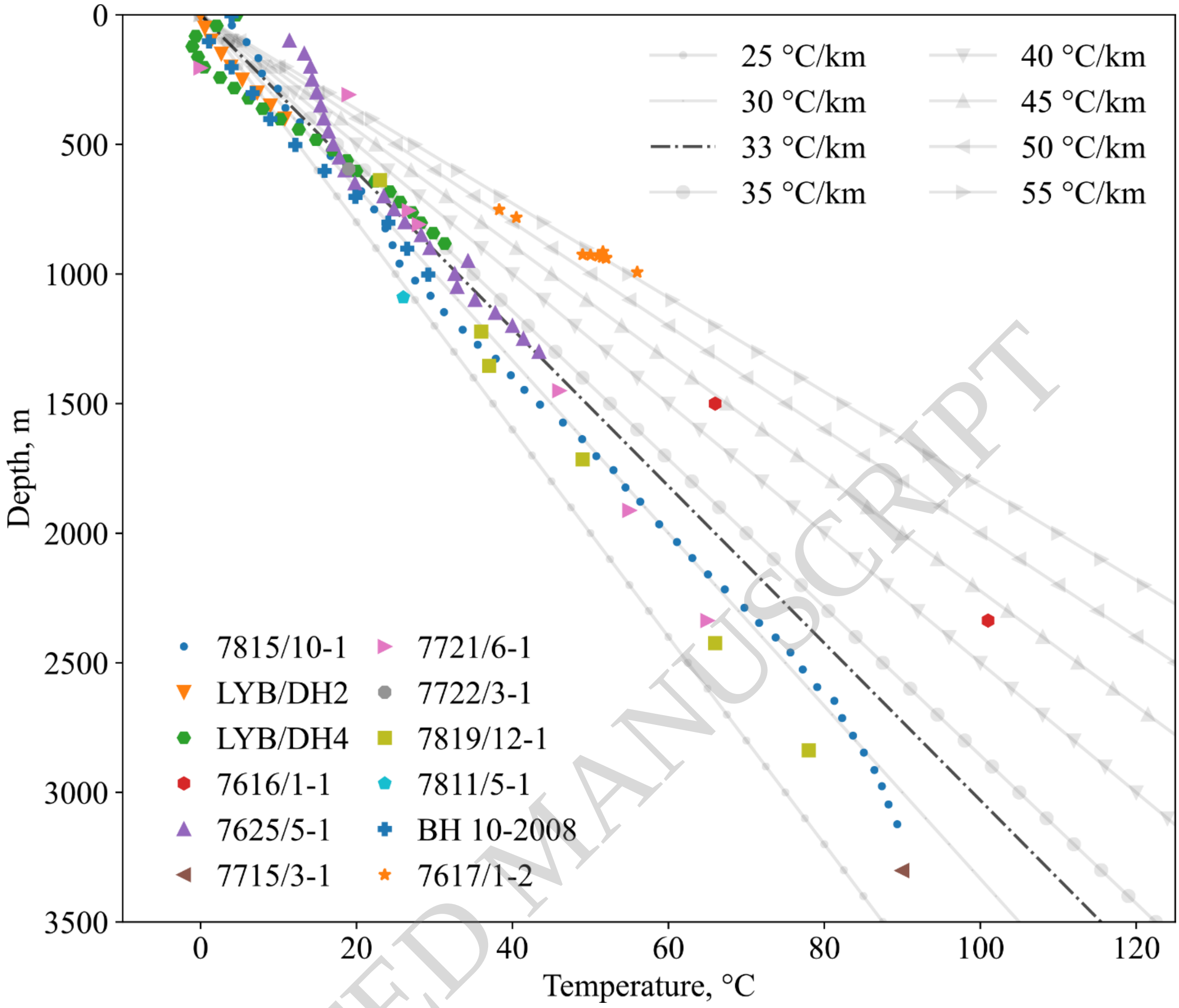

25 °C/km
30 °C/km
33 °C/km
35 °C/km
40 °C/km
45 °C/km
50 °C/km
55 °C/km
7815/10-1
LYB/DH2
LYB/DH4
7616/1-1
7625/5-1
7715/3-1
7721/6-1
7722/3-1
7819/12-1
7811/5-1
BH 10-2008
7617/1-2
Depth, m
Temperature, °C
0
500
1000
1500
2000
2500
3000
3500
0
20
40
60
80
100
120

Figure 7

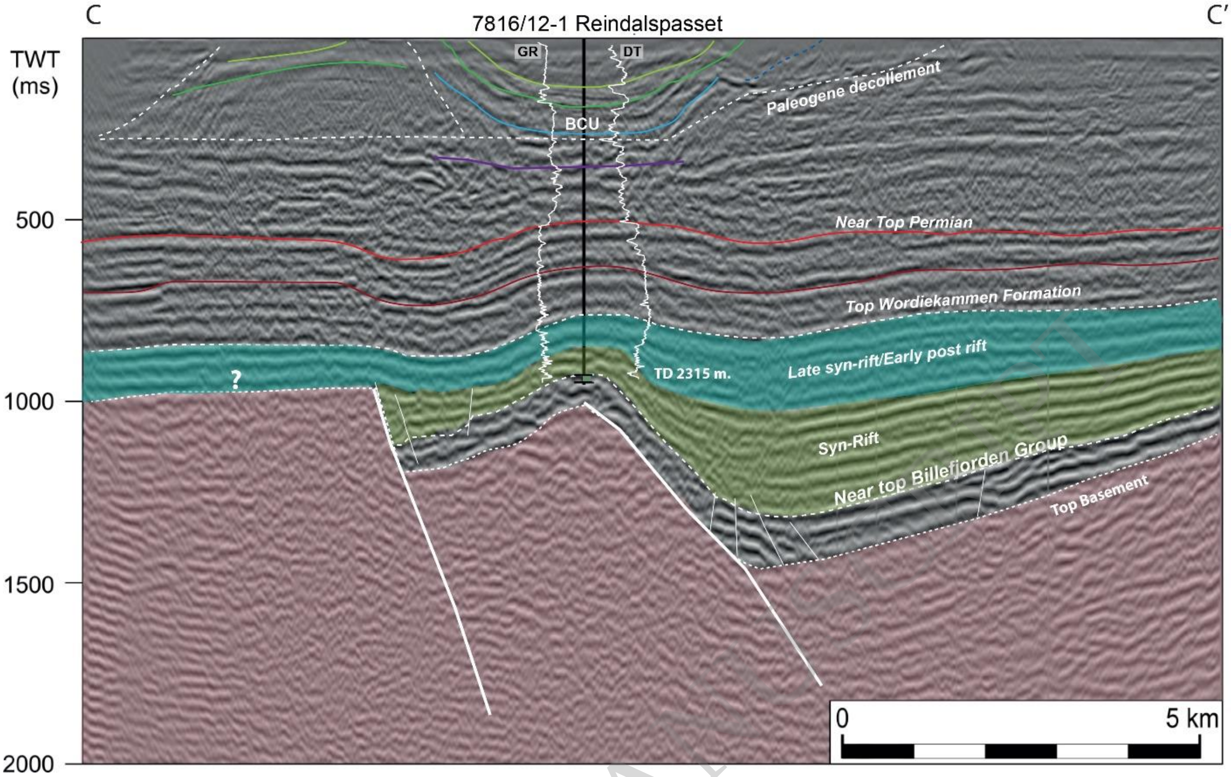

C
7816/12-1 Reindalspasset
C′
TWT (ms)
GR
DT
BCU
Paleogene decollement
500
Near Top Permian
Top Wordiekammen Formation
Late syn-rift/Early post rift
TD 2315 m.
?
1000
Syn-Rift
Near top Billefjorden Group
Top Basement
1500
0
5 km
2000

Figure 8

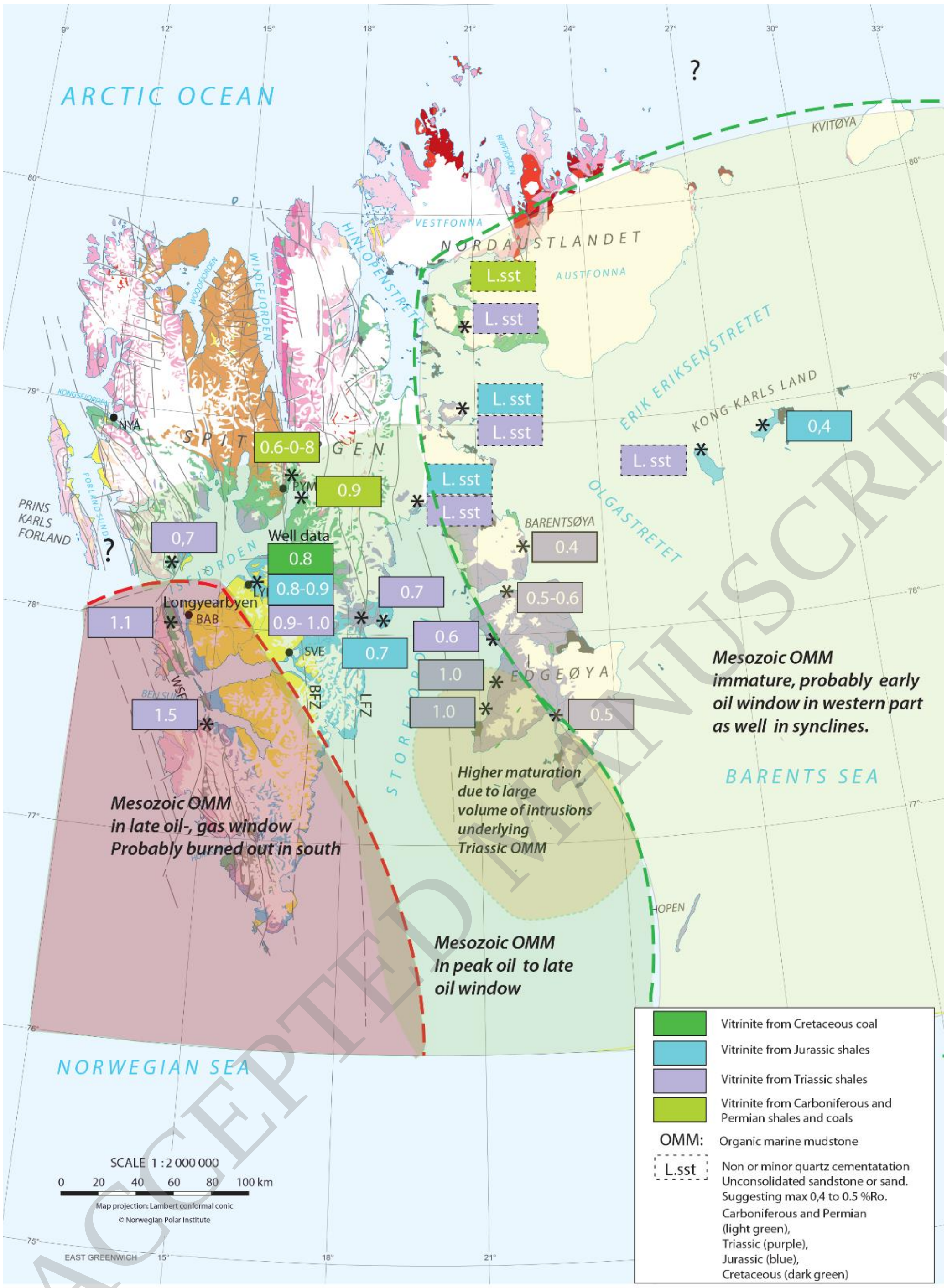

ARCTIC OCEAN
NORDAUSTLANDET
SPITSBERGEN
BARENTS SEA
NORWEGIAN SEA
PRINS KARLS FORLAND
KONG KARLS LAND
ERIK ERIKSENSTRETET
OLGASTRETET
BARENTSØYA
EDGEØYA
HOPEN
KVITØYA
Longyearbyen
Well data
Mesozoic OMM in late oil-, gas window Probably burned out in south
Higher maturation due to large volume of intrusions underlying Triassic OMM
Mesozoic OMM In peak oil to late oil window
Mesozoic OMM immature, probably early oil window in western part as well in synclines.
Vitrinite from Cretaceous coal
Vitrinite from Jurassic shales
Vitrinite from Triassic shales
Vitrinite from Carboniferous and Permian shales and coals
OMM: Organic marine mudstone
L.sst Non or minor quartz cementatation Unconsolidated sandstone or sand. Suggesting max 0,4 to 0.5 %Ro. Carboniferous and Permian (light green), Triassic (purple), Jurassic (blue), Cretaceous (dark green)
SCALE 1 : 2 000 000
0 20 40 60 80 100 km
Map projection: Lambert conformal conic
© Norwegian Polar Institute

Figure 9