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Petroleum, coal and research drilling onshore Svalbard: a historical perspective

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The beginning of the Norwegian oil industry is often attributed to the first exploration drilling in the North Sea in 1966, the first discovery in 1967 and the discovery of the supergiant Ekofisk field in 1969. However, petroleum exploration already started onshore Svalbard in 1960 with three mapping groups from Caltex and exploration efforts by the Dutch company Bataaffse (Shell) and the Norwegian private company Norsk Polar Navigasjon AS (NPN). NPN was the first company to spud a well at Kvadehuken near Ny-Ålesund in 1961. This drilling marked the start of an exciting period of petroleum exploration in Svalbard, with eighteen exploration wells drilled in the period from 1961 to 1994. The deepest well so far, Caltex's Ishøgda-I near Van Mijenfjorden, reached 3304 m in 1966. NPN was involved in nine of the eighteen wells. The remaining wells were drilled by American (Caltex/Amoseas), Belgian (Fina), French (Total), Soviet/Russian (Trust Arktikugol), Swedish (Polargas Prospektering) and Norwegian companies Norsk Hydro and Store Norske Spitsbergen Kulkompani. None of the wells resulted in commercial discoveries, though several wells encountered gas in measureable quantities. Only the two wells drilled in the early 1990s were drilled on structures defined using a sparse 2D seismic grid, while the other wells were drilled based on geological mapping at the surface. Furthermore, more recent research and coal exploration boreholes have confirmed moveable hydrocarbons in close proximity to the Longyearbyen and Pyramiden settlements. In this contribution, we present a historical and brief geological overview of the petroleum exploration wells onshore Svalbard. We illustrate that the eighteen petroleum exploration wells have together penetrated over 29 km of stratigraphy, with the Late Palaeozoic–Mesozoic successions particularly well covered. Coal exploration and research boreholes primarily focus on the Mesozoic–Cenozoic successions. As such, the boreholes represent an important window to decipher the stratigraphic evolution of both Svalbard and the greater Barents Shelf.

Keywords: Spitsbergen, hydrocarbons, Barents Shelf, drilling, history, petroleum geology, coal, scientific drilling

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Introduction

The high Arctic Svalbard archipelago was discovered by the Dutch navigator Willem Barentsz in 1596 and has attracted explorers for centuries, including geologists and entrepreneurs motivated to exploit Svalbard's natural resources such as coal and various minerals (Harland et al., 1976; Harland, 1997a; Elvevold, 2015). Less known, however,

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is that the first petroleum exploration efforts in Norway were in Svalbard, with eighteen petroleum exploration wells drilled in the period from 1961 to 1994 (Fig. 1B; Nøttvedt et al., 1993; Verba, 2007; Brugmans, 2008; Skotte, 2014b). No commercial discoveries were encountered during this campaign, but important geological data were collected that aid deciphering the stratigraphic evolution of both Svalbard (Nøttvedt et al., 1993; Harland, 1997b) and the adjoining petroleum-bearing Barents Shelf (Worsley, 2008; Henriksen et al., 2011).

Fig. 1A illustrates the high Arctic position of the Svalbard archipelago and its main islands including Spitsbergen, Barentsøya, Edgeøya, Nordaustlandet and Prins Karls Forland. Since its discovery in 1596 until 1920 Svalbard was *terra nullius*, a political no-man's land. On 9th of February 1920, the Spitsbergen Treaty (later renamed as the Svalbard Treaty; Fig. 2A) was signed in the French Foreign Ministry in Paris recognising Norway's full and absolute sovereignty of the islands situated between 74°–81°N and 10°–35°E (i.e., the 'Svalbard box'; Fig. 1A) under four main conditions: 1) Tax collected in Svalbard can only be used in Svalbard, 2) Norway must respect and preserve Svalbard's environment, 3) All citizens of signatory countries have equal right to reside, work and exploit natural resources. Norway may regulate or forbid these activities but cannot discriminate on the basis of nationality, and 4) Svalbard may not instal military bases or be used for any war-like purpose (Pedersen, 2009; Dallmann et al., 2015; Totland, 2016; Jakobsson, 2018). This has contributed to a highly international and diverse group of companies involved in the petroleum exploration. Norwegian (Norsk Polar Navigasjon AS – NPN, Norsk Hydro ASA, Store Norske Spitsbergen Kulkompani AS – SNSK), American (Caltex), French (Total), Belgian (Fina), Swedish (Polargas Prospektering AB, Petro Arctic AB) and Soviet/Russian (state-owned Trust Arktikugol) companies operated the wells. British and Dutch companies were also actively conducting geological fieldwork in Svalbard. It is notable that the geographic extent of the Svalbard Treaty is not internationally agreed upon (Pedersen, 2006, 2009; Wallis & Arnold, 2011). Norway maintains that the Svalbard Treaty is only valid onshore Svalbard and in the surrounding territorial waters (i.e., 12 nautical miles offshore). The continental shelf beyond Svalbard's territorial waters is thus wholly Norwegian, including also the prospective shelf between Svalbard and mainland Norway. The alternative interpretation of the Svalbard Treaty, favoured by Russia and other signatory countries, is that Svalbard has its own continental shelf where the same stipulations apply as onshore Svalbard (Dallmann

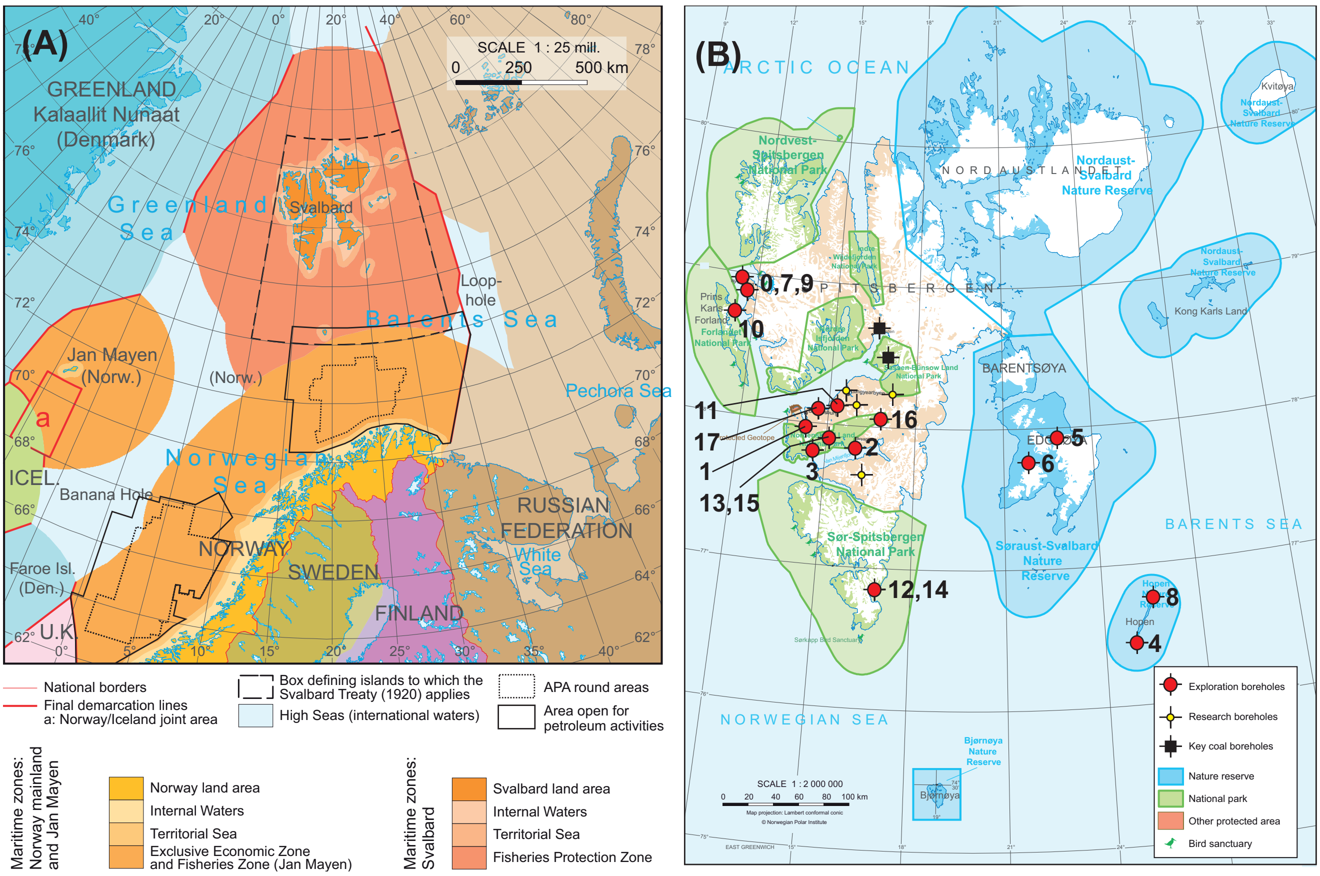

Figure 1. Figure 1. Geographical setting of Svalbard in the North Atlantic. (A) Norwegian territories and maritime zones in the Arctic. APA – Awards in predefined areas, an annual licence round in mature parts of the Norwegian continental shelf. (B) Location of key boreholes on a map of Svalbard highlighting the protected areas. The numbers represent the chronological drilling order and provide more information on the boreholes in Table 1. Both maps modified from Dallmann et al. (2015).

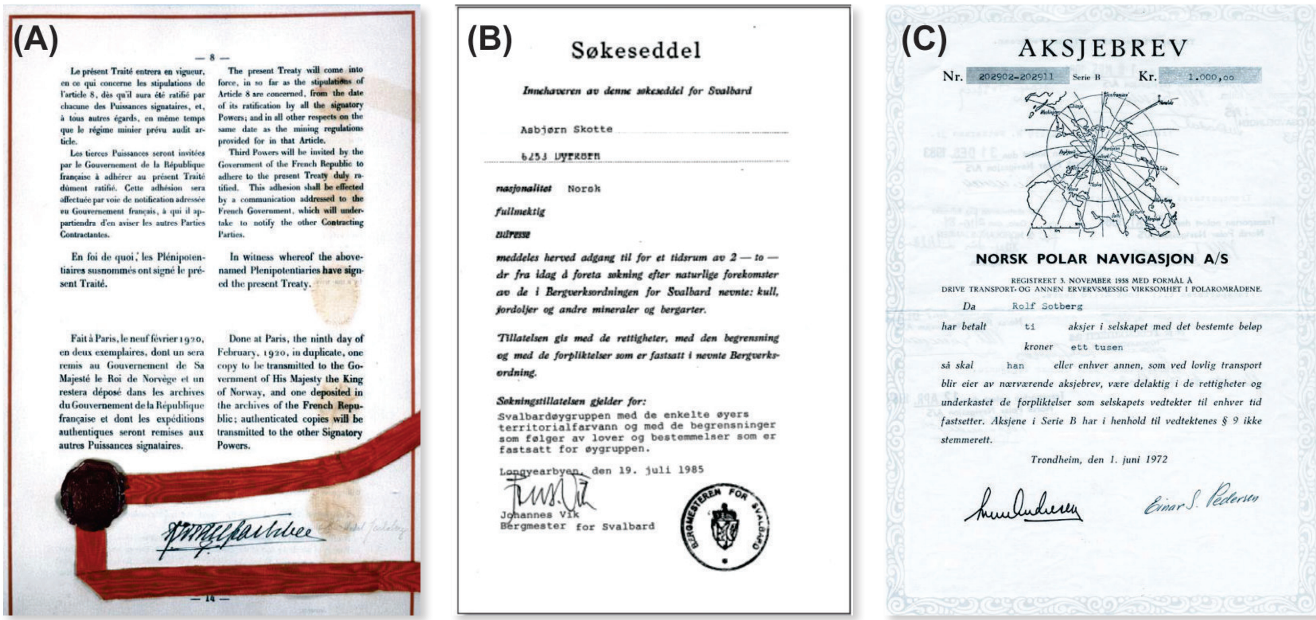

Figure 2. A selection of historical documents related to petroleum exploration in Svalbard. (A) The final page of the Svalbard Treaty. Figure from Norwegian Polar Institute archives, published by the Norwegian Ministry of Justice and Public Security (2015). (B) Example of a personal prospecting licence required to explore for resources in Svalbard, granted by the Mining Commissioner in Svalbard. Figure from Skotte (2014a). Unofficial translation: Prospecting Licence. The owner of this prospecting licence for Svalbard, Name, Address, Nationality, is granted access for 2 years from today to undertake the search for natural resources given in the Svalbard mining code: coal, petroleum and other minerals and rocks. The permission is given with the rights, limitations and the commitments as defined in the Svalbard Mining Code. The prospecting licence is valid for: The Svalbard archipelago with the island's territorial waters and with the restrictions that relate to laws and provisions which are valid for the archipelago. (C) Non-voting share certificate ('B share') from Norsk Polar Navigasjon AS, one of the key companies associated with petroleum exploration onshore Svalbard. Figure from Ianssen (2014).

et al., 2015). Totland (2016) discusses this dilemma in the context of ongoing petroleum exploration up to 74°30'N within the 23rd Barents Sea licensing round.

While geologically being a part of the Barents Shelf, Svalbard is administratively separated from both the Norwegian Continental Shelf and the Norwegian mainland. This has major implications on, for instance, data availability resulting from exploration drilling. On the Norwegian continental shelf well data are made public by the Norwegian Petroleum Directorate (NPD) two years after well completion, and interpreted data including a comprehensive well completion report are made available twenty years after well completion. In contrast, data from Svalbard remain the property of the exploration companies indefinitely, though drilling permissions for some of the later wells clearly stipulate that all geological material and reports are to be shared with Norwegian authorities. Data from Svalbard exploration wells are thus highly fragmentary, with geological data typically restricted to commercial or confidential reports (Fleming et al., 2016; Fleming & Flowerdew, 2017), fragmented datasets from data repositories or archives (Shkola, 1977; Bro, 1990a, b; Statsarkivet, 2001), few publications (e.g., Harland & Kelly, 1997; Bælum & Braathen, 2012; Anell et al., 2014b; Faleide et al., 2015), semiregional syntheses (e.g., Nøttvedt et al., 1993; Harland & Anderson, 1997; Verba, 2007) and brief exploration updates (e.g., Nagy, 1965, 1968; King, 1975; NPD, 1989).

Jakobsson (2018) provides an overview of the exploration history of the Barents Sea but only mentions Svalbard in a short passing sentence. Christiansen (2011) provides a comprehensive overview of petroleum exploration on- and offshore Greenland, where initial drilling took place in the 1970s. The history of oil exploration in Svalbard is covered in several Norwegian-language publications (Bjørklund, 2008; Brugmans, 2008; Carstens, 2014; Børresen & Carstens, 2014; Totland, 2016). Brugmans (2008) systematically covers the petroleum exploration in Svalbard, and places these in a global context. Skotte (2014b) presents an account focusing on the exploration efforts of NPN. Furthermore, numerous publications provide summaries of key geographical and geological parameters of the exploration wells (NPD, 1989, 1990; Nøttvedt et al., 1993; Harland & Anderson, 1997; Verba, 2007; DMF, 2012). However, there are some discrepancies in some of these accounts, including the number of wells, their naming convention and even their exact locations.

Thus, in this contribution we synthesise the petroleum exploration history onshore Svalbard and provide a well-by-well overview. We present updated and comprehensive tables of petroleum as well as relevant coal exploration and research boreholes (Fig. 3) to present a synthesis of

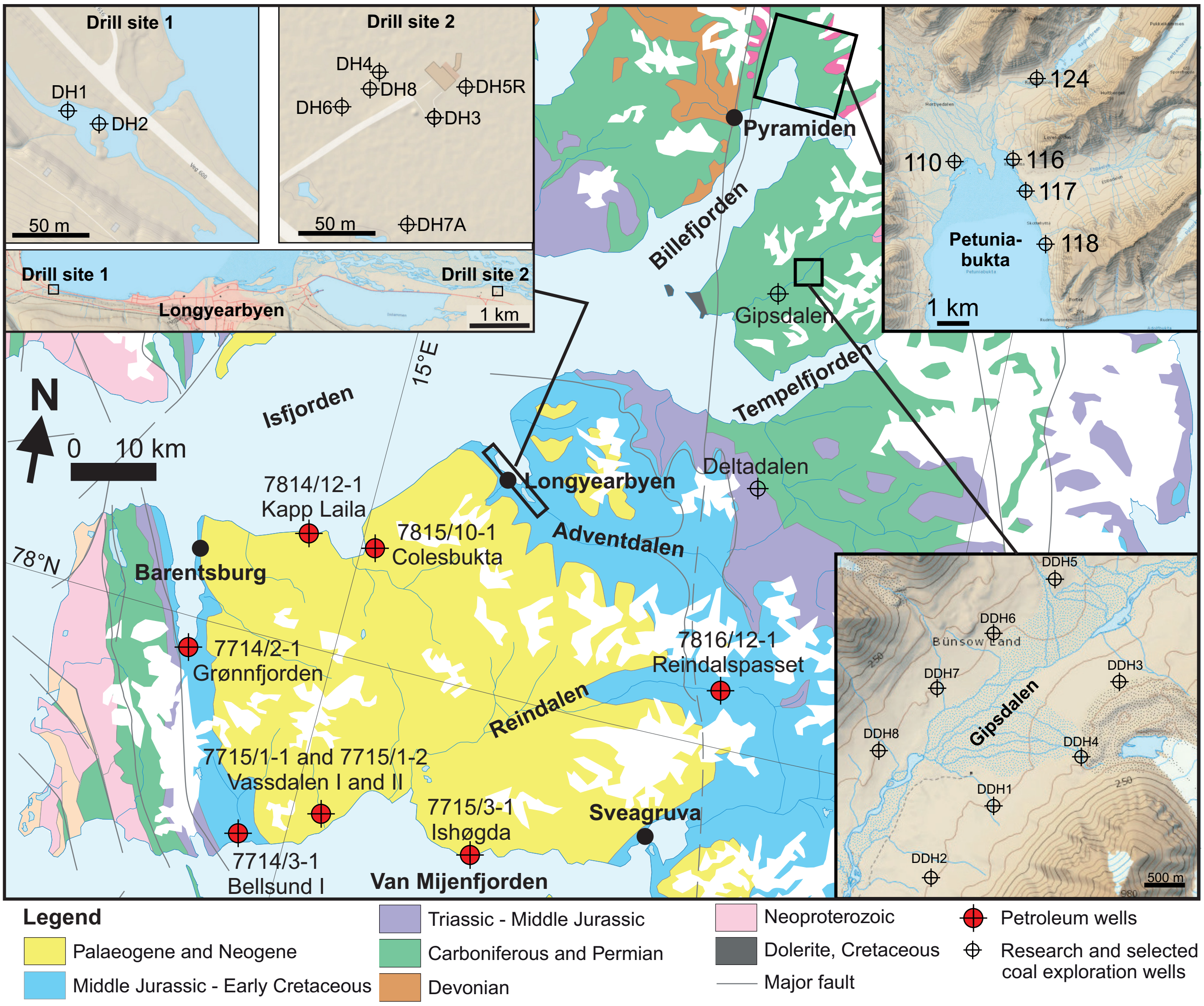

Figure 3. Geological map of central Spitsbergen illustrating the positions of petroleum exploration, research and selected coal exploration boreholes within and around the Central Spitsbergen Basin. The inset maps show the positions of the research and coal exploration boreholes listed in Table 2. Base geological map generously provided by Norwegian Polar Institute.

drill-based exploration efforts in Svalbard. Furthermore, we outline the claiming procedure in Svalbard, and try to speculate on why petroleum companies were interested in exploring the remote Svalbard archipelago.

Claiming procedure in Svalbard

Today, 65% of Svalbard's onshore area is protected as either a national park (24%) or nature reserve (41%), both of which prohibit claiming new acreage according to the Svalbard Environmental Act of 2001. As of 2018, c. 6% of the land is claimed, primarily for coal production. Notably, prior to the Svalbard Treaty, claims were not regulated by a single organisation or even nation. As a result, multiple claims covering the same area existed and claim jumping was rather common (Fig. 4A).

The procedure of obtaining claims for mineral and petroleum exploration onshore Svalbard has remained largely the same since the ratification of the Svalbard Treaty and is illustrated in Fig. 5. The authority responsible for managing claims in Svalbard and in its territorial waters is the Norwegian Directorate of Mining with the Commissioner of Mines at Svalbard (DMF), and judicially governed by the Mining Code ('Bergverksordningen for Svalbard') that came into force on 7th of August 1925 (NFD, 1925). Claim holders essentially own all resources on their claim irrespective of what they applied for. The land owner, in most cases the Norwegian state, can become involved at the exploitation and production stage with an up to 25% share. Anyone interested in prospecting onshore Svalbard must obtain a prospecting licence ('søkeseddel'; Fig. 2B) from DMF. The process involves physically marking the discovery point in the presence of at least two witnesses and delivering a discovery notice with a physical sample of the material

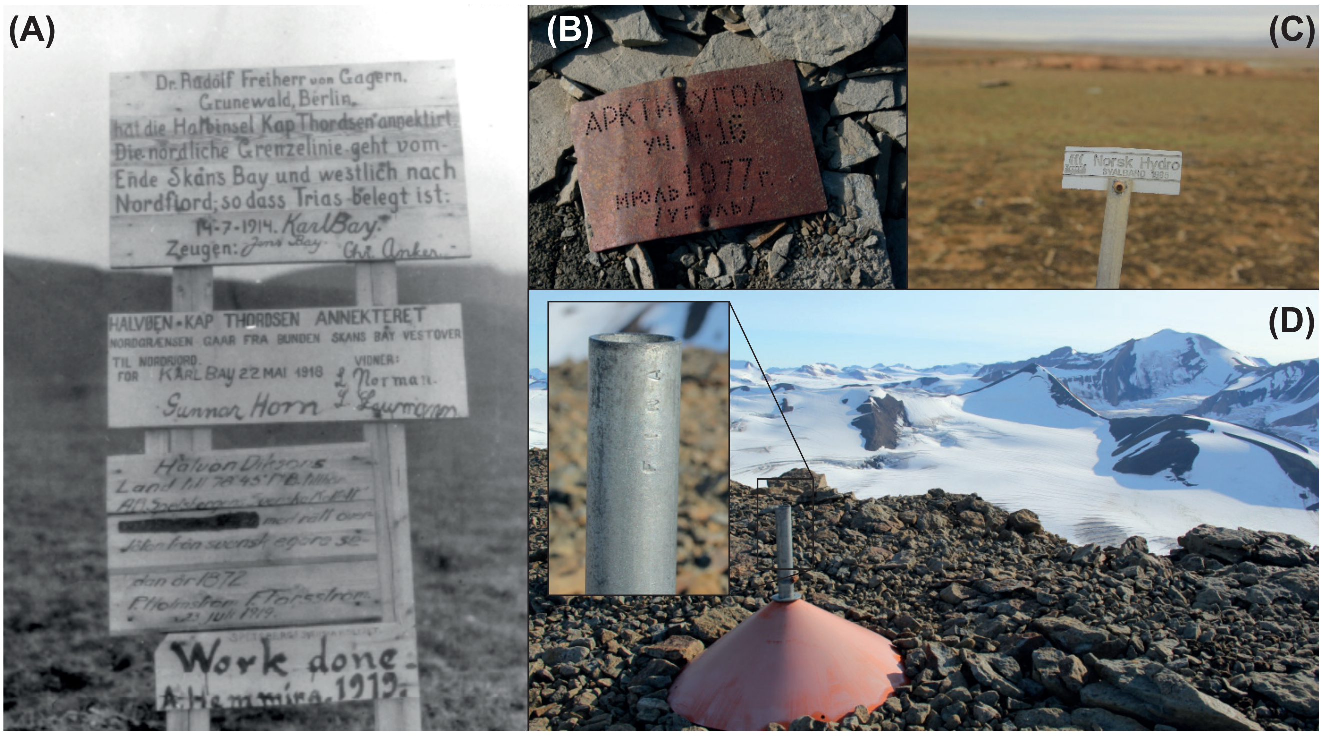

Figure 4. Past and present evidence of claiming activity in Svalbard, both for coal and petroleum exploration. A claim is not stratigraphically bounded and can be used to explore for and extract all resources present. (A) Multiple claim annexation signs at Kapp Thordsen, Isfjorden. Prior to the signing of the Svalbard Treaty it was not unusual for multiple claims in the same area. Photo from NPI photo archives, published by Elvevold (2015). (B) Discovery point placed at Wittrockfjellet north of Van Keulenfjorden by Trust Arktikugol in 1977. (C) Discovery point placed on Bjørnøya by Norsk Hydro. (D) Discovery point placed on Fotografryggen south of Van Keulenfjorden by Norske Fina. All photos except (A) by Sten-Andreas Grundvåg.

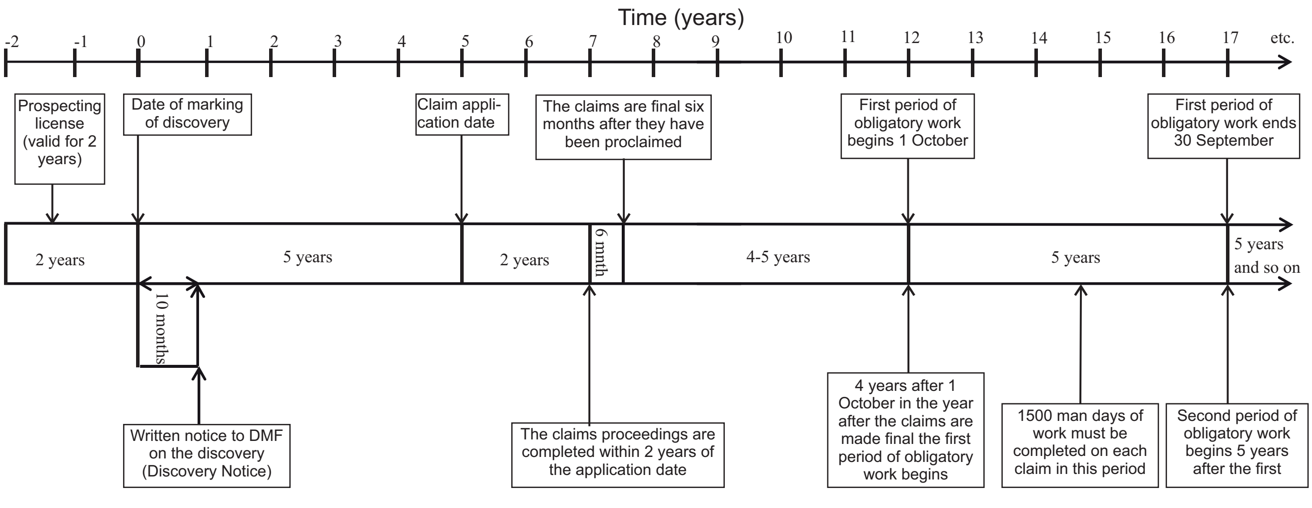

Figure 5. Timeline outlining the main events during the claiming procedure as given by the Svalbard Mining Code. Figure re-arranged from DMF (2012). DMF = Direktoratet for Mineralforvaltning med Bergmesteren på Svalbard/Norwegian Directorate for Mining with the Commissioner of Mines at Svalbard.

to the Commissioner of Mines at Svalbard within 10 months after the discovery point is marked in the field. Based on the discovery point, the Commissioner of Mines at Svalbard can issue a claim that covers up to 10 km^2. Within five years, an official claim application ('begjæring av utmål') must be submitted, followed by the claim survey ('utmålsforretning'). The claims become valid within 6 months of this event, and obligatory work periods of five years duration follow. Claims are not kept indefinitely, and activity (1500 work days per five-year period) must be demonstrated from the second work period in order to keep the claims active (NFD, 1925). In addition, a yearly cost of 6000 NOK is imposed on each claim, though this is reduced to 1500 NOK for vintage

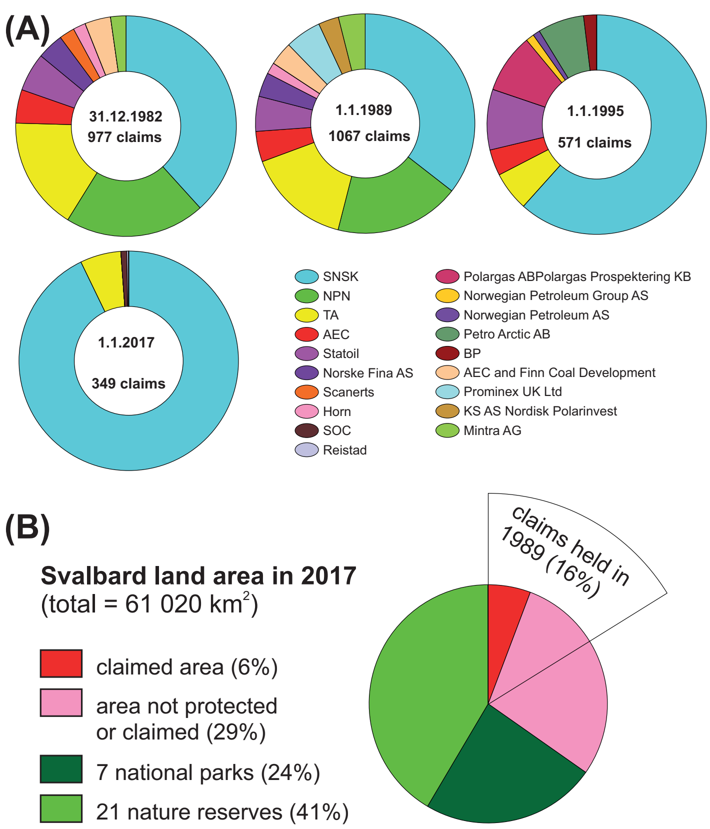

Figure 6. *(A) Detailed overview of claim statistics at four dates listing the number of claims subdivided by companies. Note that the maximum size of claims on Svalbard is 10 km². (B) Comparison of present-day status of the land area of Svalbard with respect to natural protection. Data generously provided by the Commissioner of Mines at Svalbard and the Governor of Svalbard. Company name abbreviations in (A): SNSK – Store Norske Spitsbergen Kulkompani, NPN – Norsk Polar Navigasjon AS, TA – Trust Arktikugol, AEC – Arctic Exploration Company, SOC – Svalbard Oil Company, BP – British Petroleum.*

claims presently located in national parks where activity is not permitted (Norway, 2017). Furthermore, claims that were issued in Svalbard Treaty properties are exempt from annual claim fees. There are three possibilities to keep a claim even without fulfilling the demanded workload. One is to 'distribute' workload performed in an active mine to a certain number of surrounding claims. Other possibilities are based on dispensations which might be given either if essential hindrances for operations exist, or if the owner proves that claims must be kept as reserves for claims with active mining operation. As such, the recent decision by the Norwegian government to significantly reduce coal production and essentially stop coal exploration in Svalbard poses interesting questions on what will happen to the Norwegian state-owned SNSK's extensive claim acreage covering large parts of central Spitsbergen (Finne, 2017).

For petroleum exploration, geological indications of a petroleum system comprising geological and geophysical mapping have been accepted in the past (Brugmans, 2008). In late 1960, Caltex requested to claim 201 claims based on relatively poorly documented geological indications, which were granted in 1961 (Brugmans, 2008; Totland, 2016). For Norway, this case made it impossible to refuse similar claims by Soviet (Trust Arktikugol) and private Norwegian (NPN) companies due to the non-discriminatory nature of the Svalbard Treaty, and the Caltex-case became the subject of numerous high-level political meetings between Norway and the Soviet Union (Bjørklund, 2008; Totland, 2016). More recently, DMF (2012) provides a detailed specification of how the geological and geophysical material should be presented (i.e., structure contour maps, profiles, lithological columns, etc.). In essence, the claim submitter must document the presence of a source rock capable of generating hydrocarbons, a potential porous and permeable reservoir rock and a defined trap structure. A claim is valid for all minerals and resources on the claimed property, and numerous actors thus may claim surface minerals, while in reality targetting deeper hydrocarbon prospects which are significantly more costly to document (DMF, 2012). A good example of this was the planned petroleum exploration well to be drilled in Petuniabukta, on claims initially given for coal exploration.

Claimed areas presently account for just under 6% of Svalbard's total land area, a significant reduction from 1989 when 16% of the land area was claimed (Fig. 6B). Fig. 6A illustrates the development of licence claims from 1982, which was near the peak with respect to exploration activity, to the present day. Fig. 7 illustrates

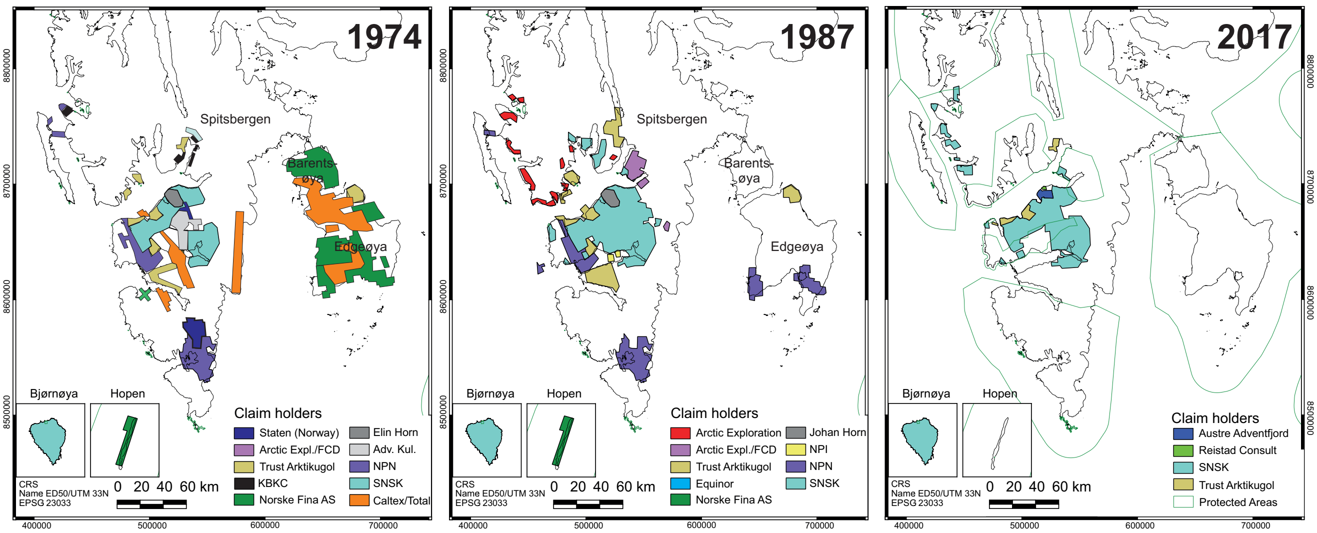

Figure 7. Maps of claimed areas for 1974, 1987 and 2017. The 1974 map redrawn from Stortinget (1975), 1987 map redrawn from Brugmans (2008), 2017 map compiled from cartographic data provided by DMF, Norwegian Polar Institute and the Governor of Svalbard. KBKC – Kings Bay Kull Compani, Adv. Kul. – A/S Adventdalens Kullfelt, NPI – Nordisk Polarinvest, NPN – Norsk Polar Navigasjon, FCD – Finn Coal Development, SNSK – Store Norske Spitsbergen Kulkompani. Some positioning uncertainty must be expected for the digitised maps.

the spatial distribution of claimed areas in 1974, 1987 and 2017. During the 1970s, large parts of Svalbard were claimed for petroleum exploration, with the eastern part particularly covered. Environmental restrictions have greatly reduced the available acreage, and the present-day map is dominated by SNSK's claims within the Central Tertiary Basin. The early 1990s saw a major shift with the drastic reduction of claims from NPN as well as significant drop in claims held by Trust Arktikugol, the Russian state-owned coal mining company. Statoil (now Equinor) released its remaining Svalbard claims in 2004 as the last major oil exploration company, and the existing claims today are dominated by those held by SNSK (Figs. 6A & 7). No petroleum-related claims are present in Svalbard since 2017. Any exploration and production activity must be carried out within the framework of the Svalbard Environmental Protection Act (Miljøverndepartementet, 2001) and in line with the relevant regulations concerning petroleum exploration (NPD, 1990).

History of petroleum exploration

Hjelle (1993), Harland (1997a), Dallmann (2015b) and Elvevold (2015) presented comprehensive overviews of the geoscientific exploration of Svalbard and Nøttvedt et al. (1993) summarised the petroleum exploration of central Spitsbergen.

Since its discovery in 1596, Svalbard has attracted numerous explorers with interest for its natural resources, and in particular Europe's rising demand for whale oil in the early 17th century resulted in systematised whaling in Svalbard. As early as 1610, whalers in Svalbard supposedly found and used coal on their ships (Dallmann et al., 2015). However, it was not until the late 1890s that commercial coal production was considered, with reputed sea captain Søren Zachariassen's 6 tonnes of coal shipped to Tromsø in 1899 representing a milestone achievement in commercial extraction of Svalbard's natural resources (Arlov, 2003; Elvevold, 2015). Permanent coal-mining communities were established in Longyearbyen (mining operation active in the period 1906–present), Grumant (1910–1962), Ny-Ålesund (1916–1962), Bjørnøya (1916–1925), Svea (1917–2016), Barentsburg (1920–present) and Pyramiden (1927–1998). Transient and less permanent coal-settlements were also established at Bohemanflya and Advent City.

The history of petroleum exploration began in 1911 when Karl Jensen, a machinist stationed at a telegraph station at Finneset near Barentsburg, observed gas and some liquid hydrocarbons bubbling from a lake near the station (Fig. 8; Brugmans, 2008). It took seven years before Jensen informed SNSK about the discovery and tried to claim it, though, unfortunately for him, SNSK had already claimed the acreage (Brugmans, 2008). It is uncertain how much gas was present in the area, but it was sufficient to allow flaring over extended periods (Brugmans, 2008). Indeed, the British oil company Northern Exploration Company Ltd. bought the gas accumulation from Jensen, even though he did not formally own it. On August 20th 1920 the company mobilised and started drilling on the site, the first oil drilling to take place onshore Svalbard. The drilling campaign was short-lived, however, as SNSK Director Karl Bay and colleagues arrived on the scene later the same day and stopped the illegal operations (Hoel, 1967b; Brugmans, 2008; Kruse, 2014; Børresen & Carstens, 2014).

Figure 8. Snapshots of the first documented petroleum discovery onshore Svalbard. (A) Gunnar Horn, geologist at NPI, standing beside the gas leak at Finneneset in 1926. Photo from NPI archives and published by Elvevold (2015). (B) Protest of a delegation from SNSK including director Karl Bay to the drilling of the British company Northern Exploration LtD on their claimed territory on 20th August 1920. Photo from SNSK archives, published by Carstens (2014).

In 1926, SNSK themselves started exploring the Grønfjorden area for petroleum. This task was assigned to the two Norwegian geologists Anders K. Orvin and Gunnar Horn. Horn was a Norwegian mining engineer graduated from the Norwegian Institute of Technology (Norges Tekniske Høgskole, now NTNU) in 1916, with further education in petroleum geology at the Royal School of Mines in London in 1920. Later, Horn worked as a petroleum geologist in Trinidad and Venezuela before going back to Norway (Brugmans, 2008). Orvin participated in many of Horn's Spitsbergen expeditions and wrote a doctoral dissertation on the geology of the Kings Bay area. In his later career he worked, amongst others as Director, at Norges Svalbard- og Ishavsundersøkelser (the forerunner of the Norwegian Polar Institute). The investigations on SNSK acreage in 1926 concluded that the methane gas in Grønfjorden was derived from coal seams in the area (Beeby Thompson, 1925; Elvevold, 2015).

Economic geological work in Svalbard from 1926 to 1960 focused mostly on coal exploration, but oil exploration in Arctic Canada and Alaska led to an increased exploration interest in other Arctic areas, including Svalbard (Nagy, 1965). Petroleum exploration onshore Svalbard started in earnest during the late 1950s (Table 1) and can be divided into four main phases (Fig. 9):

1. Phase I, from 1961 to 1968. Initial exploration and drilling by Norsk Polar Navigasjon (NPN) and Caltex/Amoseas group, culminating in four wells being drilled including the deepest well to date, 7715/3–1 Ishøgda-I.

2. Phase II, from 1971 to 1978. Continued onshore exploration and drilling by NPN. Interest and drilling by Total, Fina and Trust Arktikugol. Nine wells completed during this intense period. Marine seismic data were acquired in Svalbard territorial waters in Storfjorden by the Italian petroleum company Agip.

3. Phase III, from 1984 to 1990. Trust Arktikugol drilling in Vassdalen and Polargas Prospektering drilling at Tromsøbreen-II. Statoil is active in exploration and seismic acquisition, but not involved in drilling. Nordisk Polarinvest acquires marine seismic data, Norsk Hydro acquires onshore and offshore seismic data.

4. Phase IV, from 1986 to 1995. Quantitative and dedicated surface mapping and sampling for both petroleum and mineral exploration by SNSK and Norsk Hydro. Seismic acquisition onshore, and the drilling of two wells (Reindalspasset and Kapp Laila).

Phase I essentially started with the establishment of NPN, a Norwegian private oil company based in Trondheim. NPN was established in 1956 by the brothers Einar Sverre Pedersen (1919–2008) and Gunnar Sverre Pedersen (1922–2008) with 30,000 NOK in start capital, and only the brothers had 'A' shares allowing voting rights, with the remaining 'B' shares not eligible to vote (Fig. 2C). Einar Sverre was chief navigator at SAS specialising in long-distance polar air routes, while Gunnar Sverre was a lieutenant colonel and civil engineer with airport construction as a speciality (Bjørklund, 2008; Børresen & Carstens, 2014). NPN's initial plans of establishing an all-year civilian airport on Brøggerhalvøya near Ny-Ålesund were initially supported by the Norwegian authorities, though they were sceptical to the financing model and timeline proposed by NPN (Bjørklund, 2008). The Soviet

Table 1. *Summary of petroleum exploration wells drilled onshore Svalbard, see Fig. 1B for locations. Data updated and partly corrected from previous summaries (NPD, 1989, 1990; Nøttvedt et al., 1993; Harland & Anderson, 1997; Johannesen & Stenløkk, 2004; Verba, 2007; DMF, 2012; Ianssen, 2014) and Norwegian Polar Institute's online Svalbardkartet. UTM locations are given in WGS84 datum, UTM zone 33X north. Latitude and longitude provided in the WGS84 datum. Cores or cuttings are confirmed and located from Sarstangen, Hopen-I, Hopen-II and Reindalspasset boreholes only, but may exist for other boreholes as well. Verba (2007) and other Russian publications utilise Russian borehole names which are not always direct translations. For the sake of clarity, these are listed here: Грёнфьорден – 7714/2–1 Grønfjorden-I, Исхёгда – 7715/3–1 Ishøgda-I, Фритьофбреен – 7714/3–1 Bellsund-I, о.Надежды-1 – 7625/7–1 Hopen-I, Раддедален – 7722/3–1 Raddedalen, Плюрдален – 7721/6–1 Plurdalen, Кваденхукен-1 – 7811/2–1 Kvadehuken-I, Кваденхукен-2 – 7811/2–2 Kvadehuken-II, о.Надежды-2 – 7625/5–1 Hopen-II, Сарстанген – 7811/5–1 Sarstangen, Грумантская-1 – 7815/10–1 Colesbukta, Тромсебреен-1 – 7617/1–1 Tromsøbreen-I, Вассдален-2 – 7715/1–1 Vassdalen-II, Вассдален-3 – 7715/1–2 Vassdalen-III, Хакетанген-1 – 7617/1–2 Tromsøbreen-II. Abbreviations for operating companies: NPN – Norsk Polar Navigasjon AS, Caltex/Amoseas – California Asiatic Oil Company and Texaco Overseas Petroleum/American Overseas Petroleum, TA – Trust Arktikugol, CFP – Compagnie Française des pétroles (now Total), PG – Polargas Prospektering, NH – Norsk Hydro, SNSK – Store Norske Spitsbergen Kulkompani AS.*

Nr.	NPD well ID Borehole name	Easting Northing	Longitude Latitude	Spudded Completed	(2nd season) (2nd season)	Operating company	Elevation KB (m) Total depth (m MD)	Youngest strata Youngest formation	Oldest strata Oldest formation
0	no NPD identifier Kvadehuken 0	422898 8766520	11°23'23" 78°57'03"	summer 1961 summer 1961	23.8.1962 16.06.1963	NPN	0 479	Lower Permian Gipshuken Fm	Pre-Devonian Hecla Hoek
1	7714/2-1 Grønnfjorden I	484126 8654598	14°20'36" 77°57'34"	09.06.1963 12.08.1967	- -	NPN	7,5 971,6	Lower Cretaceous Carolinefjellet Fm	Upper Triassic De Geerdalen Fm
2	7715/3-1 Ishøgda I*	522200 8640214	15°58'00" 77°50'22"	01.08.1965 15.03.1966	- -	Caltex/ Amoseas	18 3304	Paleocene Grumantbyen Fm	Lower Permian Gipshuken Fm
3	7714/3-1 Bellsund I	494099 8634927	14°46'00" 77°47'00"	23.08.1967 10.08.1981	- -	NPN	0 405	Upper Jurassic Agardhfjellet Fm	? ?
4	7625/7-1 Hopen I*	759504 8507967	25°01'45" 76°26'55"	11.08.1971 29.09.1971	- -	Fina	9,1 908	Upper Triassic De Geerdalen Fm	Middle Triassic Botneheia Fm
5	7722/3-1 Raddedalen	678885 8660293	22°41'50" 77°54'10"	02.04.1972 12.07.1972	- -	CFP	84 2823	Upper Permian Kapp Starostin Fm	Ordovician Horbyebreen Fm
6	7721/6-1 Plurdalen	659983 8638300	21°50'00" 77°44'33"	29.06.1972 12.10.1972	- -	Fina	144,6 2351	Middle Triassic Botneheia Fm	Pre-Devonian ?
7	7811/2-1 Kvadehuken I	422965 8766706	11°23'23" 78°57'03"	01.09.1972 10.11.1972	21.04.1973 19.06.1973	NPN	0 479	Lower Permian Gipshuken Fm	Pre-Devonian Hecla Hoek
8	7625/5-1 Hopen II*	766277 8535704	25°28'00" 76°41'15"	20.06.1973 20.10.1973	- -	Fina	314,7 2840	Upper Triassic-Middle Jurassic Wilhelmøya Subgroup	Middle Carboniferous Ebbadalen Fm
9	7811/2-2 Kvadehuken II	424849 8764129	11°33'11" 78°55'32"	13.08.1973 19.11.1973	22.03.1974 16.06.1974	NPN	0 394	Lower Permian Gipshuken Fm	? ?
10	7811/5-1 Sarstangen	423402 8741941	11°28'40" 78°43'36"	15.08.1974 01.12.1974	- -	NPN	5 1113	Oligocene Sarstangen conglomerate	Pre-Devonian Hecla Hoek
11	7815/10-1 Colesbukta*	500652 8671451	15°02'00" 78°07'00"	13.11.1974 01.12.1975	- -	TA	12 3180	Paleocene Basilika Fm	Lower Permian Gipshuken Fm
12	7617/1-1 Tromsøbreen I*	552582 8533671	17°05'30" 76°52'31"	11.09.1976 22.09.1976	13.06.1977 19.09.1977	NPN	6,7 990	Lower Cretaceous Carolinefjellet Fm	Upper Triassic-Middle Jurassic Wilhelmøya Subgroup

Continues

Table 1. Continued

Nr.	NPD well ID Borehole name	Easting Northing	Longitude Latitude	Spudded Completed	(2nd season) (2nd season)	Operating company	Elevation KB (m) Total depth (m MD)	Youngest strata Youngest formation	Oldest strata Oldest formation
13	7715/1-1 Vassdalen II*	504174 8639064	15°11'15" 77°49'57"	10.01.1985 14.07.1987	- -	TA	15,13 2481	Eocene Frysjaodden Fm	Carboniferous Billefjorden Gp
14	7617/1-2 Tromsøbreen II*	552650 8533697	17°05'38" 76°52'31"	20.07.1987 30.10.1987	13.06.1988 24.08.1988	PG	6,7 2337	Lower Cretaceous Carolinefjellet Fm	Lower Permian (?) Gipshuken Fm (?)
15	7715/1-2 Vassdalen III*	504174 8639064	15°11'15" 77°49'57"	28.02.1988 01.09.1989	- -	TA	15,13 2352	Eocene Frysjaodden Fm	Middle Triassic Botneheia Fm
16	7816/12-1 Reindalspasset I*	544552 8665630	16°56'31" 78°03'28"	17.01.1991 11.04.1991	- -	NH/SNSK	182,5 2315	Lower Cretaceous Carolinefjellet Fm	Middle Carboniferous Hultberget Fm
17	7814/12-1 Kapp Laila I*	493551 8671271	14°53'38" 78°06'52"	22.02.1994 08.05.1994	- -	SNSK/TA/NH	5 503,5	Paleocene Basilika Fm	Lower Cretaceous Carolinefjellet Fm

*Wells with reported gas shows
†Wells with reported liquid hydrocarbons.
‡Wells that tested gas in producible quantities.

Union, however, saw the establishment of a large airport in Svalbard as a direct military threat during the Cold War from NATO allies, and protested immediately (Tamnes, 1992; Totland, 2016). The US-financing of the Pedersen brothers' airport plans and their close links to the US air force made it difficult to argue that their airport plans were strictly civilian (Totland, 2016). The Norwegian authorities thus stopped NPN's airport plans in 1960 and the Pedersen brothers turned to oil exploration instead. Incidentally, the all-year civilian airport in Longyearbyen was not opened until 1975. It is notable that Kvadehuken was considered as one of several possible airport sites already during the early 1950s by joint US–Norwegian intelligence (Totland, 2016).

During an airport site survey at Kvadehuken, NPN personnel noted oil traces in Carboniferous–Permian strata outcropping in the area (Børresen & Carstens, 2014), including at the planned airport site. Subsequently NPN began to secure licences in 1960 and initiated the first oil drilling in Norway with the Kvadehuken-0 well on Brøggerhalvøya in 1961 (Fig. 10; Table 1). This drilling was conducted using a cable-tool drill rig, and reached a depth of c. 500 m (Skotte, 2014a). It represents the first serious petroleum exploration drilling in Norway at the same time when the mainland oil industry was in its infancy (Gjerde, 2015). The Kvadehuken-0 well is the first of eighteen wells to be drilled onshore Svalbard during a 35-year long period (Table 1; Fig. 10).

The American, Russian and Norwegian companies were collectively awarded 401 claims in Svalbard during the period from 1960 to 1965. The drilling was preceded by geological fieldwork in the early 1960s, involving numerous field parties supported by helicopters and chartered vessels. Following the drilling operation on Brøggerhalvøya, diamond coring was applied by NPN in Grønfjorden from 1963 during the drilling of the 7714/2–1 Grønfjorden-I well which reached a depth of 972 m. The deepest well drilled to date in Svalbard is the 7715/3–1 Ishøgda-I well with a total depth of 3304 m. It was undertaken by the California Asiatic Oil Company and Texaco Overseas Petroleum Company (Caltex/Amoseas) Group on the north shore of Van Mijenfjorden in 1965–1966 (Fig. 10). Notably, the 7715/3–1 Ishøgda-I drilling took place over a year before the first exploration well was spudded (i.e., the well drilling was initiated) in the Norwegian sector of the North Sea by Esso on July 19th 1966 (well 8/3–1). Incidentally, Amoseas was awarded three exploration licenses (PL13, PL14, PL15; see www.npd.no) in the Norwegian North Sea during the first licensing round held in 1965.

The 1970s represented the boom of petroleum exploration in Svalbard and eight of the eighteen wells were drilled between 1971 and 1976, here termed Phase II. Continued activities by NPN and partners (7714/3–1 Bellsund-I, 7811/2–1 Kvadehuken-I, 7811/2–2 Kvadehuken-II, 7811/5–1 Sarstangen, 7617/1–1 Tromsø-

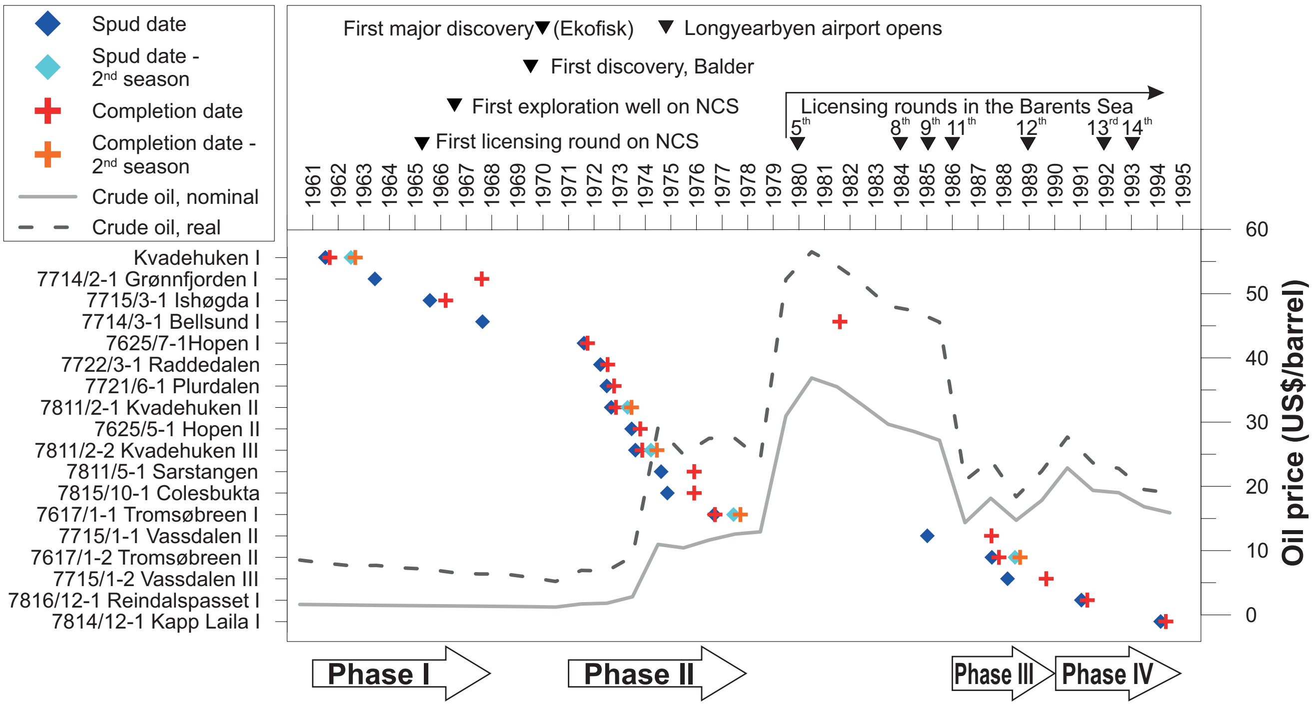

Figure 9. Timeline overview of the exploration activity onshore Svalbard from 1960 to 1995, as exemplified by exploration drilling, in the context of the global oil price (data from World Bank, 2017) and key events (most data from NPD, 2018). NCS – Norwegian Continental Shelf. For more information on the Barents Sea licensing rounds refer to Jakobsson (2018).

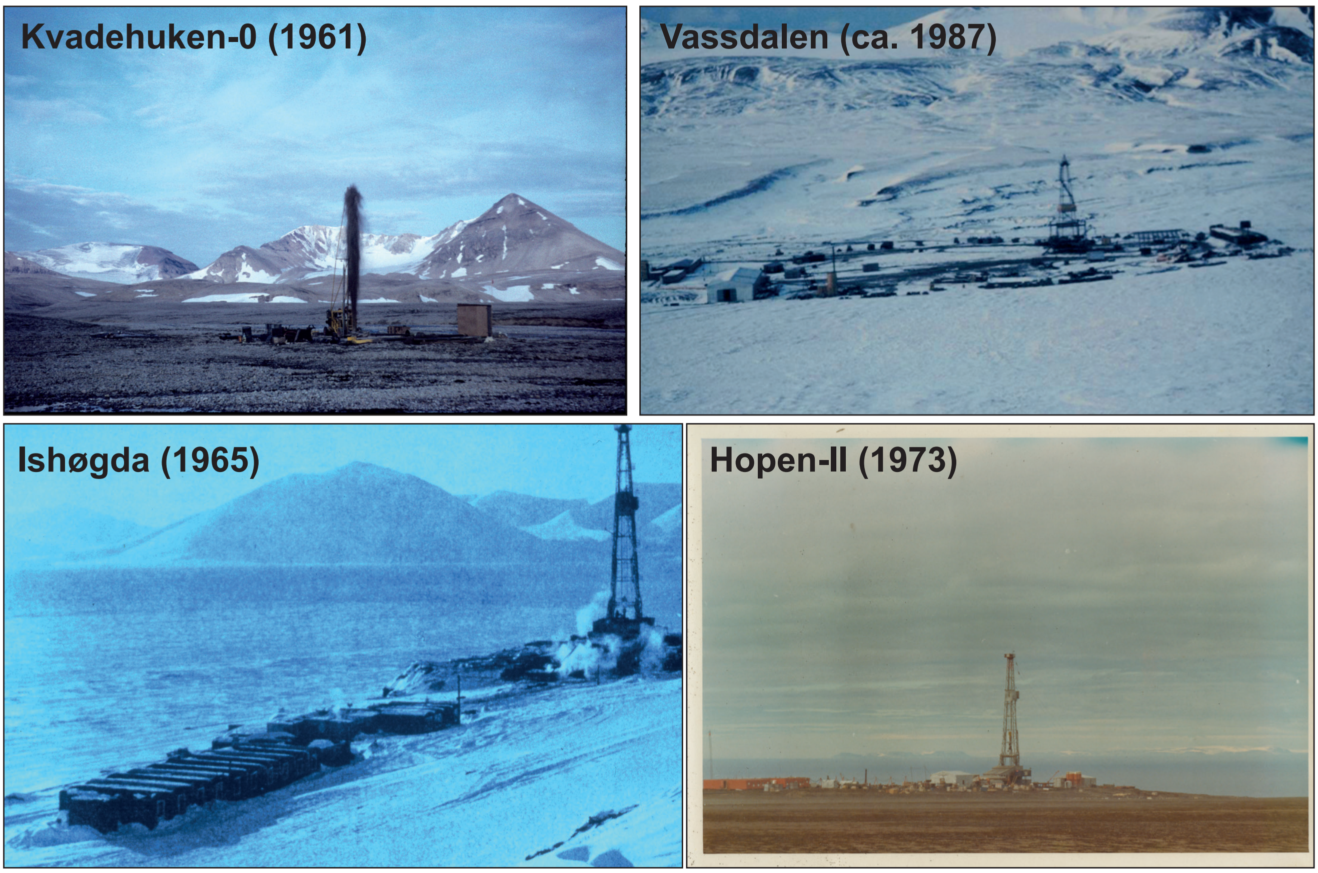

Figure 10. Snapshots from exploration drilling onshore Svalbard. Photographs from three boreholes kindly provided by Svalbard Museum. Photographers: Odd E. Gjørv (Kvadehuken-0), Carl A. Wendt (Ishøgda) and Svein Ytreland (Hopen-II) The overview image of the drilling operation at Vassdalen is reproduced from Skotte (2014b).

breen-I), the Caltex group involving Total (7722/3–1 Raddedalen) and new activity by the Belgian–French PetroFina group (7625/7–1 Hopen-I, 7721/6–1 Plurdalen, 7625/5–1 Hopen-II) were all completed before 1976. The Russian coal mining company Trust Arktikugol also started exploring for petroleum, with the 7815/10–1 Colesbukta well (1974–1975) reaching a formidable 3173 m depth (Table 1). The Italian petroleum company acquired marine seismic data in Storfjorden in 1971, and conducted detailed geological work in preparation for claim applications.

Trust Arktikugol remained a major player during Phase III of the exploration, responsible for drilling the two Vassdalen wells drilled in the mid–late 1980s, both reaching in excess of 2000 m. In addition, a major operation at Haketangen culminated in the drilling of Tromsøbreen-II in 1987–1988 by Polargas Prospektering. Some marine and land seismic was acquired during the late 1980s by Statoil who held a significant number of claims in Svalbard during this stage. In addition, Nordisk Polarinvest acquired marine seismic.

Phase IV represents the final exploration phase so far, culminating with the systematic approach by SNSK and Norsk Hydro to quantify the mineral and petroleum resource potential of all non-protected areas in Svalbard. The SNSK/Norsk Hydro campaign included an extensive surface mapping programme in 1986–1989, marine seismic acquisition in 1987 and onshore seismic acquisition in 1987–1989. Nøttvedt et al. (1993) summarised the results of these investigations, which resulted in the drilling of two wells that, in contrast to all other petroleum exploration wells in Svalbard, targeted seismically-defined closures at 7816/12–1 Reindalspasset (Fig. 10) and 7814/12–1 Kapp Laila. The strict environmental regulations associated with the passing of the Svalbard Environmental Protection Act in 2001 (Miljøverndepartementet, 2001) hampered further activity. However, Trust Arktikugol had concrete plans for petroleum exploration drilling in Petuniabukta as late as 2004.

Petroleum exploration wells

Table 1 provides an overview of the petroleum exploration wells drilled onshore Svalbard. Several of the wells have different names, particularly in Soviet/Russian and Western literature, and we thus adopt the well nomenclature from NPD (1989) based on blocks in addition to the well name to avoid ambiguity. Summaries for individual wells are provided in chronological order below. All depths in the text and Table 1 are given in measured depth relative to the elevation of the kelly bushing plate (MD RKB). The KB values vary from site to site due to drill-site elevation and the type of the drill-rig used.

Kvadehuken-0 (1961) – no NPD well identifier

There is some uncertainty with respect to the first well spudded in Svalbard for hydrocarbon exploration. NPN's activity on Brøggerhalvøya resulted in the drilling of a well at Kvadehuken as early as the summer of 1961. NPN claimed this area on the basis of oil samples washed out of surface sediments collected and analysed in conjunction with the airport plans the Pedersen brothers had in the area (Brugmans, 2008; see discussion above). The drilling operation, however, only penetrated 2 m in the first year, reaching c. 111 m in the second year (1962; Børresen & Carstens, 2014) and c. 500 m in the third year (1963; Fig. 10; Skotte, 2014b). The cable-tool drilling rig, with a drilling capacity of about 600 metres, was Norway's first oil exploration rig and was acquired by NPN in the spring of 1961 for 30,000 SEK, half paid in cash and half in NPN shares (Ytreland, 2014b). This well was not included in the hydrocarbon exploration summary published by NPD (1989) as the equipment used was light-weight and only suitable for shallow wells. Consequently, the well lacks a numeric well identifier, but is discussed elsewhere (Brugmans, 2008; Skotte, 2014b; Børresen & Carstens, 2014). We include the well due to its importance as the first exploration well drilled in Norway, the significant depth of c. 500 m, and the fact that cable-tool drill rigs were relatively common in onshore exploration in the 1960s. The well did not result in a hydrocarbon discovery, and virtually no geological information is available. Two additional wells, Kvadehuken-I and Kvadehuken-II, were drilled by NPN in the area in the 1970s.

Børresen & Carstens (2014) provide some insight into the daily operations and life in the simple working conditions at Kvadehuken. The Ytreland family, in particular, was heavily involved in NPN's annual Svalbard expeditions from 1962 onwards, being responsible for the campaign leadership and cooking for up to 15 hungry workers in a small cabin. NPN rarely had any capital to pay salaries to the workers, and much of the early drilling and Svalbard expeditions was conducted by adventure-seeking volunteers and students who were only paid travel and food expenses. Nonetheless, NPN was still a major player in Svalbard. Through its ongoing claiming campaign it subsequently became an important partner for the major oil companies interested in Svalbard.

7714/2–1 Grønfjorden-I (1963–1967)

NPN also operated the first 'official' hydrocarbon exploration well in Svalbard, the 7714/2–1 Grønfjorden-I well. It was drilled following the company's acquisition of a rotary drilling rig in 1963 from Svenska Diamantbergboringbolaget AB. The drill rig was an XH–90 rotating diamond drilling rig with a drilling capacity to about 900 metres (Ytreland, 2014a). It was spudded June 9th 1963 and was drilled over several summer seasons until the summer of 1967, when it had penetrated 971.6 m of Cretaceous–Triassic sedimentary strata (the Kapp Toscana and Adventdalen groups).

The full coring allowed detailed geological logging and analyses of for instance total organic content. Geologically, the well was placed at the foreland basin margin adjacent to the structurally complex West Spitsbergen Fold-and-Thrust-Belt (WSFB).

Annual inspections to Grønfjorden by the Norwegian working conditions authority ('Arbeidstilsynet') and the Norwegian Directorate of Mining with the Commissioner of Mines at Svalbard (DMF) commented on the lack of a blow-out preventer (Ytreland, 2014a). NPN rectified this by constructing its own blow-out preventer using left-over material from a disused gas power plant in Trondheim salvaged at a scrapyard, with the key part being a 6" flush valve weighing c. 20 kg installed at the wellhead in Grønfjorden in the summer of 1964 (Ytreland, 2014a). This was Norway's first blow-out preventer and was purchased for 15 NOK.

7715/3–1 Ishøgda-I (1965–1966)

Caltex/Amoseas established collaboration with SNSK to support their oil exploration activities onshore Svalbard. The 7715/3–1 Ishøgda-I well was spudded at Dom Miguelodden (sometimes referred to as Blåhuken) on the north shore of Van Mijenfjorden on August 1st 1965 and reached a depth of 3304 m (MD RKB). It remains the deepest well ever drilled in Svalbard to date. While not the first well to be drilled in Svalbard, the 7715/3–1 Ishøgda-I well represents the start of direct involvement of the supermajors in petroleum exploration in Svalbard, with state-of-the-art drilling equipment (900 tons, worth c. 20 million NOK) brought onshore in spring 1965 (Brugmans, 2008). The drill rig with the 50 m-high drilling tower stood over a number of barracks that could house up to 42 workers (Fig. 10; Brugmans, 2008). The drilling operation was hampered by fuel shortage following one of the fuel barges sinking during a storm, and the strongly lithified Tertiary sedimentary strata, both contributing to budget overspending. The total well cost, following 211 days of drilling, was almost 2.9 million USD (Brugmans, 2008).

Geological data were kept secret, resulting in a range of speculations in the media (Brugmans, 2008). The Ishøgda-I well was spudded in Paleogene infill (the Van Mijenfjorden Group) of the Central Tertiary Basin (CTB) and covers the entire Mesozoic succession, terminating in Permian carbonates of the Tempelfjorden Group. The well encountered minor traces of gas (Nøttvedt et al., 1993; Verba, 2007), though it is uncertain in which geological interval. Verba (2007) suggests Triassic–Permian strata but provides no details. Reservoir sandstones are present in Lower Cretaceous and Upper Triassic–Middle Jurassic strata (i.e., the Adventdalen and Kapp Toscana Groups), while regional source rocks are penetrated in the Middle Triassic and the Upper Jurassic successions. A 63 m-thick igneous intrusion of presumably Early Cretaceous age is present within the Middle Triassic Botneheia Formation shale, and exhibits a well-developed contact-metamorphic aureole. Some marine seismic data were acquired in 1963 in preparation for the drilling, but the hard and high-velocity sedimentary rocks made seismic processing difficult. The well was thus drilled primarily on the surface geological expression of an anticlinal structure (e.g., Dalland, 1979). Subsequent seismic mapping suggests that the well was drilled off-structure, and several prospects have been defined in the adjacent Van Mijenfjorden, with the so-called Joker structure supposedly holding a potential 35 million barrels of oil (Nordic Petroleum ASA, 2008).

Even though the well resulted only in minor gas shows, the 7715/3–1 Ishøgda-I well nonetheless represents a major achievement as it helped to better define the stratigraphic correlations from west to east Svalbard. In addition, the proximity to vintage and more recent seismic data make the Ishøgda-I well an important tie point for regional seismic interpretation in Van Mijenfjorden (Nøttvedt, 1994; Faleide et al., 2015; Knudsen, 2015) and forward seismic modelling of outcrops (Johansen, 2013). This outcrop-well-seismic correlation is facilitated by the nearly complete and relatively good-quality wireline logging suite.

7714/3–1 Bellsund-I (1967)

The 7714/3–1 Bellsund-I well (sometimes referred to as Berzeliusdalen or Fridtjofbreen) was drilled by NPN following the completion of the 7714/2–1 Grønfjorden-I well in 1967. The drilling took 299 days and was conducted over several summers due to technical challenges. The well reached a final depth of 405 m, likely within the shales of the Upper Jurassic–Lower Cretaceous Agardhfjellet Formation (lowermost part of the Adventdalen Group). It is perhaps best known for featuring a home-made blow-out preventer, and the drill rig itself is today exhibited at the Svalbard Museum in Longyearbyen (Stenløkk, 2006). As with the 7714/2–1 Grønfjorden-I well, the 7714/3–1 Bellsund-I well was located at the foreland margin of the structurally complex WSFB and only limited geological material is presently available.

7625/7–1 Hopen-I (1971)

The 7625/7–1 Hopen-I well was drilled by the Belgian Fina-group, which also included NPN, in the summer of 1971 on the southern tip of the island of Hopen (Fig. 1B). It penetrated 908 m of Triassic strata, culminating in shales of the Middle Triassic Botneheia Formation (the Sassendalen Group). Initial biostratigraphic analyses based on 11 samples were presented by Harland & Kelly (1997), and the limited wireline data suite (gamma ray available from 0 to 645 m, otherwise no data) makes detailed correlation challenging. Nonetheless, a revisit of the core material resulted in a recent updated report from Cambridge Arctic Shelf Programme (Fleming et al., 2016), though this is unfortunately confidential.

7722/3–1 Raddedalen (1972)

The 7722/3–1 Raddedalen well was spudded by Compagnie Française des Pétroles (CFP; now Total) and its partners on Edgeøya on April 2nd 1972. It penetrates Triassic, Permian and Carboniferous strata in the uppermost 874 m, reaching a total depth of 2823 m. The Permian-aged carbonates in the uppermost part have some porosity, averaging about 5% though up to 13–15% in some thin layers. One such relatively thin (2–3 m thick) layer demonstrated relatively high permeability with a flow rate of fresh water of 1200 m^3/day (Verba, 2013). No hydrocarbons were encountered in the well. At least four coal seams of c. 1.5 m thickness each are present in the Lower Carboniferous part of the penetrated succession, referred to as the Billefjorden Group (Bro & Shvarts, 1983).

The lower part of the stratigraphy in the well is currently unresolved; biostratigraphic ages based on analyses of drilling cuttings presented by Bro & Shvarts (1983) and Shvarts (1985) suggest a thick Early Silurian and Ordovician-aged, limestone-dominated package (i.e., the Sørkapp Land Group?) from a depth of 874 to 2823 m, based on a sampled conodont *Drepanodus*. The Cambridge Svalbard Exploration group, however, suggests on the basis of independent palynological observations that the lower part of the well is probably Early Carboniferous to Late Devonian in age, and thus part of the Billefjorden Group (Harland & Kelly, 1997). Notably, the two groups worked independently of each other, with fragmented data that were the result of data trading between the different licence groups operating in Svalbard at the time (Harland & Kelly, 1997). Clearly, these contrasting interpretations have major implications on the understanding of the tectonic evolution of eastern Svalbard, and notably the tectonic structuration during the Carboniferous rifting phase. Further work is required to geophysically delineate a hypothetical tectonic lineament between the two boreholes, and try to reanalyse any remaining cuttings or core material if these still exist. The cabin used during the geological fieldwork on Edgeøya, 'Caltexhytta', is still standing on the northern shore of Diskobukta and represents an important cultural heritage element as little infrastructure remains from the oil exploration activity (Sandodden, 2013).

7721/6–1 Plurdalen (1972)

The 7721/6–1 Plurdalen well is located 29 km southwest of the Raddedalen well, approximately 20 km from the coast along the valley Plurdalen at an elevation of c. 145 m. It was spudded on June 29th 1972 by Norske Fina, with NPN as a partner. The well penetrates 2351 m of Triassic to potentially pre-Devonian strata. The upper section comprises c. 118 m of shale-dominated units of the Sassendalen Group with the boundary to the Kapp Toscana Group more or less at the terrain surface. The well further penetrates the cool-water carbonates and spiculites of the Tempelfjorden Group, the warm-water carbonates of the Gipsdalen Group and reaches the base of the sandstone-dominated Lower Carboniferous Billefjorden Group at c. 841 m MD. A gradual increase in resistivity within the Gipshuken Formation in the upper part of the Gipsdalen Group coincides with the base permafrost transition zone, and could be related to a shallow gas accumulation capped by the permafrost, though no hydrocarbons have been reported from the well.

The deeper part of the well is inferred, on the basis of cuttings and selected cores, to comprise Devonian sandstones, with the lower c. 500 m potentially of pre-Devonian age based on the lack of spores (Harland & Kelly, 1997). The wireline signature, however, suggests minimal variation across this interface with a gradual increase in resistivity and sonic velocity suggesting reduction of porosity with depth. There is a marked difference in the wireline signature of the pre-Carboniferous strata in the Plurdalen and Raddedalen wells, as also discussed by Harland & Kelly (1997).

7811/2–1 Kvadehuken-I (1972) and 7811/2–2 Kvadehuken-II (1973)

Following the first well drilled by the cable tool rig in 1961–1962 (Kvadehuken-0), NPN drilled two more wells on Brøggerhalvøya in the early 1970s with a rotary drilling rig capable of full coring. The 7811/2–1 Kvadehuken-I well was spudded on September 1st 1972 and completed on June 19th 1973, after two drilling seasons. The 7811/2–2 Kvadehuken-II well was spudded on August 13th 1973 and completed on June 16th 1974. Both wells reached relatively shallow depths, 479 and 394 m respectively, and did not encounter any hydrocarbons. The wells, approximately 3200 m apart, are located in the WSFB and both penetrate Permian–Carboniferous carbonates. Very limited geological data are available from this campaign. The Kvadehuken-I borehole penetrates metamorphic basement (Hecla Hoek) at 470 m depth. The boreholes were fully cored as evidenced on photographs but it is, unfortunately, unclear whether any physical drillcore material from the wells is still available. The Geopol cabin used by NPN during the Brøggerhalvøya drilling operations remains onsite and is currently used by the welfare group of the Ny-Ålesund research community.

7625/5–1 Hopen-II (1973)

The 7625/5–1 Hopen-II was spudded on the northern tip of Hopen by Fina on June 20th 1973. The well penetrated 2823 m of Triassic to middle Carboniferous strata, and represents an important calibration well for seismic interpretation south and east of Edgeøya (e.g., Anell et al., 2014b), seismic modelling of Kvalpynten (Anell et al., 2016), as well as regional correlation (Harland & Kelly, 1997). Wireline log quality is good and available completion logs are well documented. Traces of gas (methane and ethane, up to 7% for methane) were encountered throughout the Triassic section. In the Permian section only traces of methane and ethane were encountered, though significant amounts of H_2S were recorded. Detailed analysis of the well is presented in a confidential report by CASP (Fleming & Flowerdew, 2017).

Notably, the interest in Hopen as an analogue to the petroleum systems in the southwestern Barents Sea sparked renewed interest in 2002, when Norwegian Petroleum Group claimed licences on the southern part of the island. The ambition was to drill and fully log a c. 3 km deep stratigraphic well, the data from which could be sold to companies operating on the Barents Shelf (Skotte, 2014b). However, shortly after the licence was claimed, Hopen became a protected nature reserve in 2003, resulting in an abrupt and effective end of the exploration of the island.

7811/5–1 Sarstangen (1974)

The 7811/5–1 Sarstangen well is the deepest well operated by NPN and was drilled in 1974 on the eastern margin of the Forlandsundet Graben to a depth of 1113 m (Fig. 11A). The well penetrates an approximately 1 km-thick, monotonous succession of interbedded shales and siltstones with subordinate sandstones and thin conglomerates, belonging to the Eocene–Oligocene Buchananisen Group. At the base, the well penetrates 67 metres of folded and metamorphic rocks, mostly schists, belonging to the pre-Devonian basement (Dallmann, 1999). Cores have been taken at four stratigraphic intervals, and the well has also been included in a regional study of Oligocene deposits on the Norwegian Continental Shelf (Eidvin et al., 2014). Gas was encountered in thin sandstones, with 3800 m^3/day reported in what remains the world's northernmost technical hydrocarbon discovery (King, 1975).

7815/10–1 Colesbukta (1974)

The 7815/10–1 Colesbukta well was drilled in 1974–1975 by the Russian coal mining company Trust Arktikugol, and reached a total depth of 3180 m. In literature, the well is referred to as Grumantskaya (Verba, 2007), Grumant-1 (Nøttvedt et al., 1993; Eiken, 1994) or Grumantbyen (Anell et al., 2014a), all referring to the nearby coal mining settlement of Grumant.

The penetrated geology is summarised by Shkola et al. (1980). Shkola (1977) summarises the drilling and sampling operation, and provides a wider range of data particularly on the geochemistry (e.g., TOC) of the penetrated sedimentary succession and as well as the tested gas (Shkola, 2007). The well penetrates Paleocene, Cretaceous, Jurassic, Triassic and Permian strata and thus represents an important regional correlation well linking western Spitsbergen with the eastern Svalbard platform province. Thrust faulting particularly along Upper Jurassic and Middle Triassic shale-dominated décollement zones has resulted in both missing and repeated sections as evidenced by wells, outcrops and seismic data. An igneous intrusion of likely Early Cretaceous age is evident in middle Triassic shales of the Bravaisberget Formation, displaying a well-developed metamorphic aureole. Similar intrusions are also penetrated in the 7715/3–1 Ishøgda-I and the two Vassdalen wells (Shipilov & Karyakin, 2010), in the DH4 borehole in Adventdalen (Senger et al., 2014), and are widely exposed in outcrops around Svalbard.

Verba (2007) reports gas flow in two intervals within the Triassic, with production of up to 10,000 m^3/day (interval 2156–2200 m; Anisian succession) and 6000 m^3/day (interval 2340–2375 m; Olenekian succession). Published free gas analyses suggest a methane-nitrogen mixture with a minor contribution of ethane in the Triassic interval (Shkola, 2007).

7617/1–1 Tromsøbreen-I (1976)

NPN drilled the 7617/1–1 Tromsøbreen-I well in remote southeastern Spitsbergen over two seasons from September 11th 1976 to September 19th 1977. NPN used the same drilling rig as employed at 7811/5–1 Sarstangen in western Spitsbergen, which involved a major logistics operation involving boats and helicopters that took the large part of the summer of 1976 (Skotte, 2014b).

The well reached a depth of 990 m and was completed in reservoir sandstones of the Upper Triassic–Middle Jurassic Wilhelmøya Subgroup. Minor gas shows were encountered during drilling through the Lower Cretaceous Rurikfjellet Formation of the Adventdalen Group. In addition, a well kick, related to sudden pressure release during drilling, with associated gas flow was reported within the Wilhelmøya Subgroup at 960 m depth. NPN planned to drill the well deeper but struggled with financing the operation (Skotte, 2014b), and it was not until 10 years later that the Tromsøbreen-II well was spudded in the area.

7715/1–1 Vassdalen-II (1985) and 7715/1–2 Vassdalen-III (1988)

Trust Arktikugol drilled two deep wells in Vassdalen on the north shore of Van Mijenfjorden, the 7715/1–1 Vassdalen-II and 7715/1–2 Vassdalen-III wells (Fig. 11B). The objective of the drilling was to gain a better regional understanding of the northwestern Barents Shelf, and provide geological reference points to assist in interpreting geophysical data (Bro, 1990a). As such, the wells must be considered primarily to represent stratigraphic boreholes. However, testing of the hydrocarbon potential in Triassic sandstones was reported as a secondary objective (Eisenhardt, 1990).

The first well penetrated Paleocene and Mesozoic strata and was completed in the Lower Carboniferous Billefjorden Group at 2481 m, with numerous large-scale thrust faults contributing to missing stratigraphy. Some datasets of the penetrated lithology, stratigraphy and total organic content, amongst others, are published in an online data repository (Bro, 1990a, b). Verba (2007) states that both wells resulted in natural gas flow from Triassic strata, with up 3000 m^3/day, though there are some discrepancies in the reported depths. At least 8 cores were taken from the 7715/1–1 Vassdalen-II well. In addition, 44 (Vassdalen-II) and 68 (Vassdalen-III) samples were analysed for density, magnetic susceptibility and porosity (Bro, 2007a, b). The highest porosity encountered was 5%, whereas the majority of samples encountered porosities of <1%.

7617/1–2 Tromsøbreen-II (1987)

The 7617/1–2 Tromsøbreen-II well (sometimes referred to as Haketangen) was spudded on July 20th 1987 by Swedish company Polargas Prospektering KB (previously known as Svensk Polarenergi AB). This company entered the petroleum exploration onshore Svalbard by securing a 50% share of 76 exploration licences held by NPN in return for fully financing an exploration well to at least 3000 m depth (Skotte, 2014b). The German drilling company Deutag was hired as the drilling entrepreneur, while Polargas Prospektering KB acted as operator.

The well reached a formidable depth of 2337 m and was likely completed in the carbonates of the Lower Permian Gipshuken Formation (upper part of Gipsdalen Group). Recent reports and witness reports (Ron Gartner, Nils Martin Hanken, pers. comm., 2019) suggest that the well terminated in pre-Caledonian basement rocks, but the wireline data are not conclusive in the matter and final drill reports are not available. Gas was tested in several stratigraphic levels, and the drilling results also suggested an increased potential in large anticlinal structures towards the northwest (Skotte, 2014b), the Hornsund Anticlinorium. Minor gas was tested from Permian carbonates in the well (DMF, 2012). The wireline dataset is much more comprehensive than the fragmentary data available from the nearby 7617/1–1 Tromsøbreen-I well.

7816/12–1 Reindalspasset-I (1991)

The 7816/12–1 Reindalspasset-I well was spudded on January 17th 1991 by Norwegian exploration and production company Norsk Hydro AS, in collaboration with SNSK and Swedish company Petro Arctic AB, and represents the first time that an exploration well was drilled onshore Svalbard on the basis of seismic data. Bælum & Braathen (2012) present the well along a 2D seismic profile acquired by Norsk Hydro in 1988, clearly illustrating the targeted subsurface anticline directly associated with two underlying fault strands of the Billefjorden Fault Zone (BFZ), a N–S-trending regional lineament in eastern Spitsbergen.

The well was completed in sandstones and shales of the Early Carboniferous Hultberget Formation (lower part of the Gipsdalen Group) at a depth of 2315 m. The well was dry but encountered minor gas shows (Nøttvedt et al., 1993). Core retrieval of reservoir sandstones at TD showed very low porosity and permeability. Norsk Hydro was the technical operator of the well. The German drilling company Deutag was contracted as drilling entrepreneur, whereas SNSK provided all logistics services, including mobilisation and demobilisation of approximately 3000 tonnes of equipment from Svea to Reindalen and back. All equipment was transported by bulldozers and sledges along the frozen riverbeds of Kjellstrømdalen – Lundstrømdalen – Reindalen. Imposing Norwegian offshore safety standards, in addition to complex logistics operations and technical drilling challenges, resulted in a total well cost in the range of 100 mill. NOK.

7814/12–1 Kapp Laila-I (1994)

The 7814/12–1 Kapp Laila-I well represents the last well to be drilled onshore Svalbard specifically for petroleum exploration, and was spudded on February 22nd 1994. It was drilled by SNSK with supervision from Norsk Hydro on area claimed by the Russian company Trust Arktikugol (Fig. 11C). The well's objectives were to test the reservoir and source potential of primarily the Paleogene Van Mijenfjorden Group and the Jurassic–Cretaceous Adventdalen Group, and specifically test a large-scale fault-propagation fold known to exist from surface mapping (Elvevold, 2015).

The well reached a depth of 503.5 m and was terminated in the Paleocene Basilika Formation. Verba (2007) suggested that gas logging data indicate a gas-bearing horizon near the base of the well. The drilling was nonetheless suspended before reaching its intended target of the Helvetiafjellet Formation for technical reasons.

Non-petroleum related boreholes

Table 2 summarises selected boreholes drilled for research and coal exploration. Some of these boreholes, notably the Russian coal exploration drilling in Petuniabukta and the University Centre in Svalbard's (UNIS) research drilling campaign in Adventdalen, encountered mobile hydrocarbons. The research boreholes in particular provide full coring and good wireline coverage, allowing regional correlation and quantitative assessment of the physical properties of the different strata in Svalbard. Drillcores acquired by SNSK and UNIS are available in Longyearbyen, while physical samples (i.e., cuttings, drillcores) from the petroleum exploration boreholes are either distributed in numerous repositories in Norway and abroad or lost. The Svalbard Rock Vault initiative aims to systematise these fragmentary datasets for enabling future research activities (Jochmann et al., 2019).

Devonian and Carboniferous coal exploration on Bjørnøya

On Bjørnøya, coal deposits of Devonian and Carboniferous age were mined during several periods during the late 19th and early 20th centuries. Drilling was performed at eleven locations on Bjørnøya in order to map the coal seams and to obtain a stratigraphic overview. Horn & Orvin (1928) described nine of the eleven boreholes. In

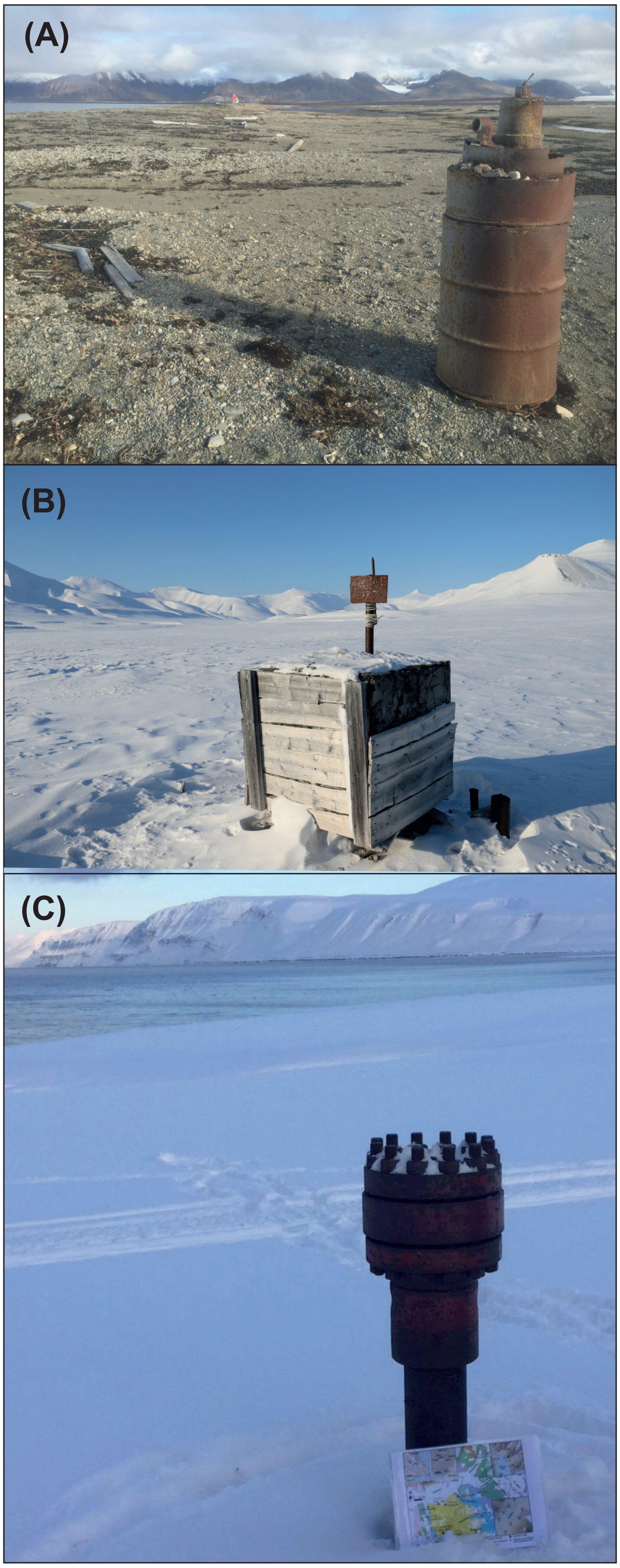

Figure 11. Selected well heads as they appear today. (A) Sarstangen borehole with the lighthouse in the background, August 2018. Photo by Kim Senger. (B) Present-day evidence of exploration activity at the Vassdalen-II borehole. Photo by Sten-Andreas Grundvåg. (C) Kapp Laila borehole, March 2019. Note the Grumantbyen thrust fault in the background. Photo by Kim Senger.

the first half of the 1920s, the Norwegian government, after a proposal by the Ministry for trade and industry, financed a topographic and geological mapping campaign on Bjørnøya. According to Hoel (1967a), the island was the best explored area in the polar regions after that campaign. From 1924 to 1925, the last four boreholes with a cumulative length of 760 m were drilled. The mining commissioner of Svalbard, H. Merckoll, was in charge of the drilling which was performed by the Norwegian company Norsk Diamantborings A/S (Horn & Orvin, 1928). Today, most of Bjørnøya is a protected nature reserve. The land owner is Bjørnøen AS, a company owned by the Norwegian state. SNSK holds claims on the entire island.

Exploration boreholes in Petuniabukta

Lower Carboniferous coal was explored in Pyramiden from 1910 by the Swedish company AB Isfjorden–Bellsund (later taken over by AB Spetsbergens Svenska Kolfält and Svenska Stenkolsaktiebolaget Spetsbergen) and subsequently by the Russian companies Russkij Grumant (from 1927 to 1930) and Trust Arktikugol (from 1930 to 1998). With declining coal resources in the Pyramiden mountain, at least 12 exploration wells were drilled by Trust Arktikugol in the late 1980s to early 1990s to map the distribution of coal seams in the inner part of Billefjorden. The exploration wells penetrate over 1200 m of mixed carbonate-evaporate-siliciclastics of Serpukhovian to Moscovian age, representing the synrift basin fill succession of the Billefjorden Trough (Johannessen & Steel, 1992; Smyrak-Sikora et al., 2018).

Limited geological information is available from six of the boreholes (Table 2; Fig. 3). Verba (2013) presents lithostratigraphic profiles of two deep wells (110 and 116; Fig. 2), reaching formidable depths of 1228 m and 1290 m, respectively. Light liquid moveable oil near the gas condensation window was reported in two wells (wells 116 and likely 117 at 684 m depth; Fig. 3) by Verba (2007), who also estimates the resource potential on the order of 'tens of tons'. At least two boreholes experienced uncontrolled gas blow-outs with some oil reaching the surface (Fig. 12; Stenløkk, 2006). In well 116, the oil discovery is reported at the depth of 631 m in the sandstones of the Bashkirian Ebbadalen Formation (Verba, 2007). This oil is likely sourced from the underlying coal deposits, based on a chromatographic analysis (Verba, 2007), and according to media reports 22 litres of oil were recovered (Mogård, 2003). Interestingly, it took almost eight years for Norwegian authorities to find out about this discovery (Mogård, 2003). For five wells that reached at least the Bashkirian-aged stratigraphy Verba (2007) suggests that the flow of combustible gas had a production rate of about 200 m^3/day. In general, gas clusters and oil and gas alternations occur in a wide range of depths from 200 to 1225 m, merging into a number of productive horizons (Verba, 2007).

Table 2. *Summary of relevant exploration drilling conducted for research and coal exploration onshore Svalbard. Coal exploration boreholes targeting the Paleogene Firkanten Formation are excluded for clarity. The location of the Gipsdalen boreholes is based on digitised and georeferenced maps, and some inaccuracies must be expected. The location of the Billefjorden boreholes is based on Verba (2007) and Verba (2013), as well as the Norwegian Polar Institute's online map 'Svalbardkartet'. All positions are given in WGS84 datum, UTM zone 33X north. The appendix A/B in the Gipsdalen campaign signifies boreholes where technical difficulties required a re-entry at the same position. Cores are available for coal exploration, UNIS CO_2 lab, Deltadalen and the shallow Gipsdalen boreholes. Abbreviations for operating companies UNIS – University Centre in Svalbard, TA – Trust Arktikugol, SNSK – Store Norske Spitsbergen Kulkompani, EBE – E&B Explorations Ltd., Canada, AEC – Arctic Exploration Company A/S, Norway, GT – Grundstofftechnik GmbH, Germany.*

Borehole name	Easting Northing	Spudded Completed	Operating company	Elevation KB (m) Total depth (m MD)	Youngest age Youngest formation	Oldest age Oldest formation
Selected coal exploration stratigraphic wells in the Billefjorden area						
Well 116*† (oil discovery at 631m)	534352 8739174	1989 1991	TA	13 1290	Moscovian Minkinfjellet Fm	Caledonian Hecla Hoek
Well 116 bis*	534409 8739031	unknown unknown	TA	14 unknown	Moscovian Minkinfjellet Fm	unknown unknown
Well 110	532917 8738588	unknown unknown	TA	5 1228	Moscovian base Wordiekammen Fm	Serpukhovian Hultberget Fm
Well 117*† (oil discovery)	534886 8738022	1989 1991	TA	1 unknown	Moscovian Minkinfjellet Fm	unknown unknown
Well 118	535409 8736485	unknown unknown	TA	5 711	Moscovian Minkinfjellet Fm	unknown Minkinfjellet or Ebbadalen Fm
Well 124	535241 8741322	unknown unknown	TA	56 unknown	Bashkirian Ebbadalen Fm	unknown unknown
Relevant coal/uranium exploration stratigraphic wells in the Gipsdalen area						
DDH 1A / 1B* (3-750 SA / SB)	544429 8718114	07.07.1978 28.07.1978	EBE sub-operators AEC & GT	48,43 97.10 / 210.50	Ebbadalen Fm	Billefjorden Group
DDH 2 (4-750 S)	543665 8717236	1978	EBE sub-operators AEC & GT	49,22 243,90	Ebbadalen Fm	Billefjorden Group
DDH 3A / 3B (1-750 S)	545969 8719628	1978	EBE sub-operators AEC & GT	61,64 11.00 / 95.25	Ebbadalen Fm	Precambrian (Cambro-Silurian?) Basement
DDH 4 (2-750 S)	545504 8718708	1978	EBE sub-operators AEC & GT	78,57 132,00	Ebbadalen Fm	Precambrian (Cambro-Silurian?) Basement
DDH 5 (1-750 N)	545196 8720868	1978	EBE sub-operators AEC & GT	86,60 91,90	Ebbadalen Fm	Precambrian (Cambro-Silurian?) Basement
DDH 6 (2-750 N)	544446 8720228	1978	EBE sub-operators AEC & GT	67,78 180,55	Ebbadalen Fm	Precambrian (Cambro-Silurian?) Basement
DDH 7A / 7B (3-750 N)	543761 8719532	1978	EBE sub-operators AEC & GT	53,47 210.15 / 210.10	Ebbadalen Fm	Billefjorden Group
DDH 8 (4-750 N)	543039 8718782	1978 03.09.1978	EBE sub-operators AEC & GT	55,60 209,60	Ebbadalen Fm	Billefjorden Group
Well "Gipsdalen"	518885	unknown	unknown	ca. 20 min 750		Precambrian (Cambro-Silurian?) Basement

Continues

Table 2. Continued

Borehole name	Easting Northing	Spudded Completed	Operating company	Elevation KB (m) Total depth (m MD)	Youngest age Youngest formation	Oldest age Oldest formation
Selected research wells						
BH 10-2008 (Sysselmannbreen)	524557 8617239	27.04.2008 13.06.2008	SNSK	408,5 1085	?Eocene-?Oligocene Aspelintoppen Fm	Late Paleocene Basilika Fm
DH2 (CO2 lab project)	512446 8684765	11.10.2007 03.12.2007	UNIS	1,8 856,3	Early Cretaceous Carolinefjellet Fm	Late Triassic-Middle Jurassic De Geerdalen Fm
DH4* (CO2 lab project)	518885 8681102	24.08.2009 27.11.2009	UNIS	6,1 969,7	Early Cretaceous Carolinefjellet Fm	Late Triassic-Middle Jurassic De Geerdalen Fm
DH5R* (CO2 lab project)	518940 8681093	09.07.2012 10.08.2012	UNIS	5,8 702	Early Cretaceous Carolinefjellet Fm	Late Triassic-Middle Jurassic De Geerdalen Fm
DH7A* (CO2 lab project)	518903 8681006	29.05.2012 02.07.2012	UNIS	6,3 704	Early Cretaceous Carolinefjellet Fm	Late Triassic-Middle Jurassic De Geerdalen Fm
Deltadalen 1 (DD-1)	542440 8688450	05.08.2014 09.08.2014	Arctic Drilling	146 99,3	Early Triassic Vikinghøgda Fm	Late Permian Kapp Starostin Fm
Deltadalen 2 (DD-2)	542440 8688450	05.08.2014 09.08.2014	Arctic Drilling	146 92,9	Early Triassic Vikinghøgda Fm	Late Permian Kapp Starostin Fm

*Wells with reported gas shows.
†Wells with reported liquid hydrocarbons.
‡Wells that tested gas in producible quantities.

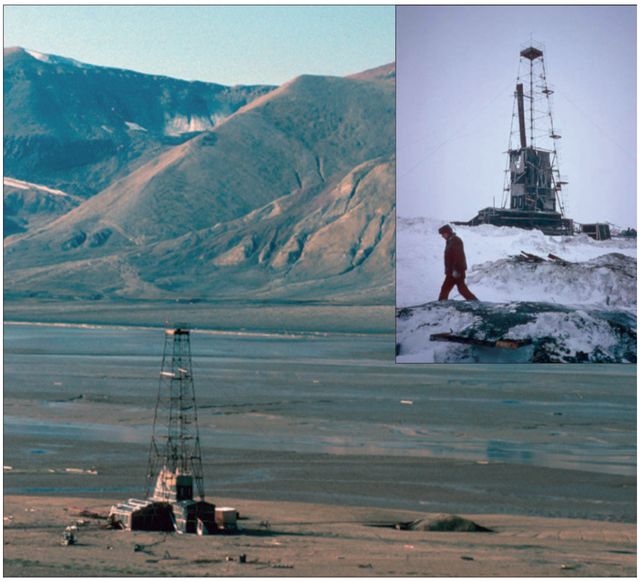

Figure 12. *Russian rig in Petuniabukta, Billefjorden, where coal drilling in 1991 resulted in gas blow-outs and small amounts of oil reaching the surface. Photo by Winfried Dallmann, Norwegian Polar Institute, 1993, published by Elvevold (2015). The inset image shows the same borehole in spring conditions, photo from Kjærnet & Elvevold (2012), photographer Torfinn Kjærnet.*

Incidentally, Trust Arktikugol had concrete plans for delineating this technical petroleum discovery by drilling an exploration borehole to 1300–1600 metre depth in 2004–2005 on the eastern shore of Petuniabukta (Mogård, 2003). Though the environmental restrictions were significantly tightened as the Svalbard Environmental Protection Act came into force on 1. July 2002, the application for drilling was submitted by Trust Arktikugol to the Governor of Svalbard before this law was established and it seemed likely that the permission would be granted, even with numerous environmental concerns voiced by, for instance, the Norwegian Polar Institute (Aftenposten, 2004). Clearly, this borehole was never drilled, though it remains uncertain whether this was for economic, environmental or other reasons. According to a letter from Trust Arktikugol to the Governor of Svalbard on 24.5.2004, the contracted drilling operator Arktikneft could not carry out the drilling operation and an alternative drilling operator would certainly not have been able to start the drilling during 2004. The claims held by Trust Arktikugol on the eastern shore of Petuniabukta lapsed in 2017 and there are no current plans for petroleum exploration in the area.

Exploration boreholes in Gipsdalen

The Scottish Spitsbergen Syndicate (SSS) examined the coal-bearing strata of the Lower Carboniferous Billefjorden Group in Ebbadalen, Brucebyen and Gipsdalen during the first half of the 20th century. Several drillholes with depths down to 60 metres were drilled as early as 1922 (Hoel, 1967a).

In the late 1970s, a joint venture between the Canadian E&B Explorations Ltd., the Norwegian Arctic Exploration Co. A/S and the German Grundstofftechnik GmbH culminated in the drilling of 11 boreholes in Gipsdalen (Table 2; Fig. 3; Grundstofftechnik GmbH, 1979). The drilling target was twofold: Firstly, black shales of the Billefjorden Group were to be examined for their uranium content (inspired by findings of uraniferous shales at age-equivalent strata at Triungen). Secondly, coal horizons were to be mapped in order to construct four cross-sections across Gipsdalen and make resource calculations. The boreholes were drilled and cored with two Longyear 34 drill rigs (maximum capacity 350 m) between June and September 1978 and reached depths between 92 and 244 m. The cumulative drilled section was 1691.96 m, with a recovery rate of more than 95% and a core diameter of 45.2 mm.

During the campaign, the Finnish company Suomen Malmi Oy was the drilling contractor, German Grundstofftechnik GmbH was responsible for geological work, geological mapping and coal exploration, and Norwegian Arctic Exploration Co. A/S was responsible for all logistics, local administration, drilling supervision and a topographic survey while E&B Explorations Ltd. was the operator. DDH no. 3, 4, 5 and 6 (Fig. 3) reached the metamorphic basement that, according to the drill logs by Dr. N. Weißenbach from Grundstofftechnik GmbH, consists of intensively folded mica schists dominated by muscovite and chlorite with cm-wide quartz veins. The other drillholes terminated in Lower Carboniferous strata of the Billefjorden Group. The permafrost was in average 200 metres thick. Porous rocks below the permafrost contained water under high pressure of 23 bar at the drill head, indicating a pressure of around 45 bar at the bottom. Gas occurred in one drillhole (DDH no. 1B). The targeted uranium anomalies were not detected during the campaign. The reserve estimate for potential mineable coal, in other words the technically recoverable and economically feasible part of the resources, was 9.6 Mtons recoverable washed coal within the permafrost zone with seam thicknesses exceeding 0.8 m. Below the permafrost, estimates were considerably higher, but due to the encountered difficulties with high pressures, mining operations were considered to be too demanding. The coal with a vitrinite reflectance between 1.07 and 1.21% proved to be suitable for coke production.

After the 1978 campaign, Grundstofftechnik GmbH and E&B Exploration sold their shares (totalling 67%) to Finn Coal Development (FCD). Arctic Exploration Co. kept their 33% of the shares. FCD was founded by four Finnish state-owned companies, among them Neste Oy and Outokumpu, in order to tackle the challenges associated with an increased coal consumption in Finland and supply problems of coal from Poland. The Norwegian state indicated a willingness to participate in mining operations with a 25% share, thereby exercising the rights of the land owner according to the Mining Code for Svalbard.

During a subsequent drilling campaign in 1982, 12 to 16 boreholes were planned in the same area as the 1978 campaign with a tighter grid. Two Longyear 38 drill rigs were used with aluminum T–56-rods, the same as SNSK used in coal exploration. Suomen Malmi Oy was again the operator, and about 80% of the planned drillholes were successful (SNSK, 1982). No detailed report about the results of the drilling campaign, which was initially planned to last three years, was available to the authors.

By the end of the decade, the claims in Gipsdalen were bought by the British company Northern Resources Ltd. who intended to commence coal mining in Gipsdalen in the early 1990s, and commissioned an extensive environmental survey (Brekke & Hansson, 1990). Financial difficulties for the company, however, prevented the coal mine establishment (Kruse, 2014). Since September 2003, the area is part of the Sassen-Bünsow Land National Park and therewith, all activities related to exploration or extraction are prohibited (KMD, 2003). SNSK is still today keeping six claims in outer Gipsdalen.

Deltadalen Permian–Triassic research campaign

The Deltadalen research campaign of 2015 was the last drilling conducted onshore Svalbard. Planke (2016) presents the project's operational and analytical programme, which focused on multiphysical high-resolution analyses of two fully cored boreholes across the Permian–Triassic boundary drilled at Deltadalen on the south side of Sassendalen. Data acquisition was efficient, with the two c. 100 m-deep boreholes drilled and fully cored within a week, using a helicopter-portable drill rig. Ongoing analytical programmes are designed to quantify the Permian–Triassic mass extinction, and the Deltadalen campaign may represent a role model of high-impact research conducted with minimal environmental footprint through high-resolution stratigraphic drilling.

Longyearbyen CO_2 lab wells, Adventdalen

In 2007, the University Centre in Svalbard (UNIS) initiated a project to investigate the feasibility of storing CO_2 from Longyearbyen's coal-fuelled power plant in the subsurface beneath Adventdalen (Braathen et al., 2012). By the end of the project's Phase II in 2015, documented by UNIS CO_2 Lab AS (2015), eight slim-hole boreholes were drilled, fully cored and partly wireline-logged at two drill sites in the vicinity of Longyearbyen to characterise the reservoir and cap-rock. Four of the boreholes penetrate parts of the c. 300 m-thick, naturally fractured, siliciclastic reservoir within the Upper Triassic–Middle Jurassic Kapp Toscana Group at c. 670 m depth. The other four boreholes are shallower and were drilled to systematically investigate the cap-rock properties (UNIS CO_2 Lab AS, 2015). Storage capacity is adequate for the modest local needs, fluid injectivity was demonstrated through water injection tests and the cap-rock integrity is confirmed by a major pressure difference across it (Senger et al., 2015).

Natural gas was encountered at three stratigraphic intervals during the drilling, and was analysed in both produced gas samples taken at the well head (Ohm et al., in review) and from gas extracted from drillcores at specific depths (Huq et al., 2017). The deepest well, DH4 with a depth of 972 m, produced thermogenic gas from an open-hole section from 870–972 m depth in the Upper Triassic De Geerdalen Formation (Ohm et al., in review). The nearby DH5R and DH7A boreholes also produced thermogenic gas, though with a different composition, from the reservoir cap-rock interface. Part of the shale-dominated cap-rock succession has been hydraulically stimulated during a leak-off test (Bohloli et al., 2014), and it is likely that the majority of this gas represents an unconventional shale gas accumulation (Ohm et al., in review). Finally, a biogenic-dominated gas accumulation is present directly beneath the permafrost at the CO_2 lab well site and is possibly linked to a known shallow gas accumulation c. 5 km to the southeast. Initial thermo-baric modelling suggests that some of this gas could occur in the form of natural gas hydrates (Betlem et al., 2019). The presence of natural gas has led to a major plugging and abandonment operation to prevent leakage of the deep gas to the atmosphere (UNIS CO_2 Lab AS, 2015).

Cretaceous coal exploration

Norwegian skipper Søren Zakariassen was, in 1899, the first to export coal from Svalbard (Reymert, 1999). The coal was a mixture of Cretaceous coal from Bohemanneset (Helvetiafjellet Formation) and Paleogene coal (Firkanten Formation) from the Grønfjorden area.

Even though several smaller coal pits and mines were active during several periods in the 20th century, targeted exploration drilling for Cretaceous coal deposits has been limited. In 1967, SNSK drilled one hole in Adventdalen at the Bolterdalen valley mouth to specifically explore the Cretaceous coal resources of the Helvetiafjellet Formation. The hole reached a depth of 106.3 m and was abandoned after encountering gas below the permafrost. Initially this was attributed to a small gas pocket as is often found during coal exploration, but in reality turned out to be a larger reservoir from which gas did not stop flowing out of the casing. The amount of gas that escaped through the well in one year was calculated to 1.2 million m^3 in October 1968.

In 1979, SNSK drilled two more drillholes for Cretaceous coal in the valley mouths of Endalen and Todalen, respectively. One of those again encountered gas below the permafrost. Exploration drilling for Cretaceous coal was put on hold, but quite some effort was made to evaluate the gas resource in Adventdalen and quantify whether the gas might be produced. In this context, both Texaco and Statoil were invited by SNSK for further co-operation and visited the area (SNSK, 1981). The sub-permafrost gas beneath the permafrost at the nearby Longyearbyen CO_2 project drill site discussed above provides further constraints on the gas accumulation extent. Today, the 1967 borehole (BH1) is equipped with a pressure gauge and valve at the well head to avoid gas leakage. SNSK holds claims in the area.

Well BH 10–2008 (Sysselmannbreen)

The Sysselmannbreen research well (formal name well BH 10–2008) was drilled in 2008 on a glacial moraine on Nathorst Land by SNSK on behalf of a consortium including Statoil (now Equinor), Det Norske (now Aker BP) and other institutions. The well location was chosen based on 48 km of 2D seismic data (Johansen et al., 2011). Johannessen et al. (2011) provided an overview of the geological objectives and the collected data. The well was designed to provide a scale link between the subsurface and nearby outcrops such as the renowned mountains Storvola and Brogniarfjella, where seismic-scale clinoforms of Eocene age (i.e., in the upper part of the Van Mijenfjorden Group) are excellently exposed.

The well provides a complete cored succession of a clinoform package from basin-floor shale at the base, via the overlying slope and shelf edge to the delta plain (Johannessen et al., 2011). The well is 1085 m deep, and reaches the Basilika Formation (in the Paleocene part of the Van Mijenfjorden Group). The well is fully cored, and includes a comprehensive wireline logging suite including GR, resistivity and qualitative density. As such, it has been the subject of a number of further studies linking outcrop, seismic and well observations (e.g., Grundvåg et al., 2014a, b). Eide (2012) focuses on the seismic processing but also provides a first-order well-seismic correlation panel. No hydrocarbons have been encountered during the drilling.

Paleogene coal exploration

Paleogene coal represents the cornerstone of most of the permanent settlements onshore Svalbard and its extraction has accelerated over large areas of Svalbard since the turn of the 20th century. Beside outcrop studies, diamond-core drilling has been the main source to map the Paleogene coal potential in Svalbard.

Svalbard's Paleogene coal is commonly oil-prone and has high potential to create hydrocarbons. The Norwegian resource committee published a booklet about oil extraction from Kings Bay coal (Ny-Ålesund) by a simple distillation process as early as 1924, where more than 20% of oil was produced from some raw coal samples (Rødland, 1924). Recently, similar studies were made based on coal from Longyearbyen and Sveagruva (Marshall et al., 2015a; Uguna et al., 2017). Miners from a coal mine in Barentsburg reported that oil, which derived and migrated from the Paleogene coal seam, dripped from the sandstone roof.

Kings Bay Kull Compani A/S (KBKC) drilled 5 boreholes with a total length of 434 metres in 1928 to map the coal field close to Ny-Ålesund. Logs and descriptions from this campaign are published by Orvin (1934). In 1952, two boreholes (a total of 113 metres) and in 1955, nine boreholes (a total of 604 metres) were drilled. Little is known about those. In 1976, the Norwegian drilling contractor Terranor drilled 12 boreholes on behalf of KBKC in the Ny-Ålesund area. The goal was to map the underexplored coal fields after production in the area had been terminated in 1963, as a consequence of a major explosion in the mine. The boreholes amounted to a total of 1080 metres with depths between 21 and 185 metres. The 45 mm drillcores were logged in detail by Midbøe (1985). The logs were later adapted by the Committee on the Stratigraphy of Svalbard and used as type sections in the Lithostratigraphic Lexicon of Svalbard (Dallmann, 1999). In 2016, a group of geologists consisting of Malte Jochmann, Peter Midbøe, Per Inge Myhre and Lars Eivind Augland set out to search for the drillcores from the 1976-campaign, but concluded that they were most likely dumped in the sea and therefore lost.

The Soviet and later Russian company Trust Arktikugol had several drilling campaigns on its claims. On Erdmannflya at the northern side of Isfjorden, three drillholes were placed to map the northernmost part of the Paleogene coal basin. The main drilling activity was in the area between Barentsburg and Kapp Laila, as well as between Colesdalen and Bjørndalen west of Longyearbyen.

SNSK was founded in 1916 in order to buy property owned by the American–Norwegian Arctic Coal Company. This land in the Longyeardalen area included an entire mining settlement with related infrastructure and a ready-made coal mine. Since 1916, SNSK had continuous underground coal mining operations until present, except for two years during the Second World War. Longyearbyen was in essence a company-town run by SNSK until the early 1990s.

During these more than 100 years, the company conducted approximately 100 kilometres of diamond drilling in roughly 400 coal exploration boreholes, normally fully cored. Most of the drillcores are logged, photographed and stored in a hall in Endalen near Longyearbyen. Many of the non-preserved cores are described in SNSK internal reports. The drillholes typically cover Paleocene and Lower Cretaceous strata, while several also comprise the Eocene formations. Until the early 1980s, with main activity in the 1960s to 1980s, drilling was primarily conducted close to the existing coal mines. Around Longyearbyen, special focus was on Mine 7 and Mine 3. In addition, the area between Mine 7 and Reindalen was subject to exploration drilling, and the Reindalen coalfield was roughly mapped. Around the settlement Sveagruva, focus was on mapping the coalfield Svea East, northeast of the active mine Svea Vest and the area in the lowlands around Sveagruva. In 1986, focus changed with the first drillhole penetrating the earlier assumed coalfield between Svea East and Lunckefjellet. A considerable thickness of coal uncovered what became the biggest coalfield ever found in Svalbard, the Central Field (Sentralfeltet, later the mine Svea Nord). From 1986 until 1993, drilling activity focused on detailed mapping of the Central Field, the connection to the Reindalen field and the direct vicinity of Mine 7. After the 1994 hydrocarbon exploration hole at Kapp Laila, exploration activity was shut down in SNSK, only to be resumed in 2002. The main targets from 2002 were the coalfields at Lunckefjellet, Reindalen, Ispallen and the area west of Svea Nord between Reindalen and Van Mijenfjorden. In addition, three exploration boreholes in eastern Nathorst Land contributed to the geological models. In 2008 and 2009, nine boreholes were drilled in the Colesdalen area. This campaign mapped an area which touches a relatively well mapped coalfield claimed by Trust Arktikugol, the Grumant coalfield. From 2010, the Bassen coalfield close to Longyearbyen came into focus and was mapped. In addition, the areas around the mine Svea Nord as well as the coalfields Lunckefjellet and Ispallen were drilled.

In addition to the commercial aspect, SNSK's drilling campaigns contributed to several geoscientific research projects. Several publications are fully or partly based on this drillcore material. These include studies on the Paleocene–Eocene thermal maximum (Charles et al., 2011; Cui et al., 2011; Dypvik et al., 2011; Nagy et al., 2013), paleoclimate (Schlegel et al., 2013), geochemistry and petrology of the coal deposits and their implications for burial history models and petroleum potential (Marshall et al., 2015a, b; Uguna et al., 2017) and constraints on the break-up of the North Atlantic using ash layers in the cores (Jones et al., 2016, 2017).

After the drilling season in 2014, exploration activity has been put on hold and plans to decommission the settlement Sveagruva were made. Mine 7 will produce as long as the coal is needed for the power plant in Longyearbyen. Whether coal exploration will be resumed, is unclear at present.

Petroleum exploration in Svalbard: motivation, geological risk and the environment

Why did the companies explore for petroleum in Svalbard?

With Svalbard's remoteness and harsh Arctic conditions it is certainly valid to question the motivation of the companies exploring for petroleum in Svalbard. We attribute these to three major factors:

1. The geological conditions appeared favourable to the presence of petroleum, with thick sedimentary packages with source and reservoir rocks along with surface oil and gas seeps.

2. A predictable and favourable tax regime, stipulated by the Svalbard Treaty. The relatively easy access to claims through the Svalbard Mining Code ('Bergverksordningen') facilitated the securing of exploration acreage.
3. The fact that both Norwegian and Soviet companies could over decades maintain year-round industrial activity in Svalbard and the benefit of the existing infrastructure related to the coal mining activity.

Brugmans (2008) sets the revival of petroleum exploration onshore Svalbard in the early 1960s in a global perspective, when the supermajor companies like Shell or Caltex started geological work in Svalbard. The nationalisation of the Iranian oil industry in 1951, the Suez crisis of 1956, the formation of the Organization of the Petroleum Exporting Countries (OPEC) in 1960 and the volatile political setting in the oil-rich Middle East all contributed to a shifting focus towards exploring for petroleum resources in politically stable regions relatively close to the main European and North American oil markets (Brugmans, 2008). At the same time, significant petroleum discoveries in the Netherlands (Groningen, discovered in 1959), Alaska (e.g., the supergiant Prudhoe Bay field, 1967–1968) and the Canadian Arctic contributed to an interest in Svalbard, lying only 4–5 days sailing from the main oil terminals in Europe (Brugmans, 2008).

Besides an industrial economic-driven perspective one must also consider geopolitics. The military significance of Svalbard was not fully understood at the time the Svalbard Treaty was signed in 1920, but became a major issue following the Second World War and the ensuing Cold War (Totland, 2016). In the 1960s and 1970s the Norwegian Government was concerned that there were more Soviet citizens in Svalbard than Norwegians. We might speculate that some of the large western oil companies were encouraged to explore Svalbard for resources and thereby increase their industrial presence in Svalbard. The importance of Svalbard to the USA is documented in recently de-classified CIA documents (CIA, 1976). The USA were clear that Arctic offshore area around Svalbard might contain oil comparable to the prolific North Sea and thereby represent an important politically-stable energy provider.

Svalbard as a possible petroleum province: geological risks, economics and the environment

Geologically, Svalbard represents an interesting exploration opportunity with thick sedimentary units comprising both source and reservoir rocks, similar to those targeted from 1980 in the southwestern Barents Sea. A simplified pre-drill geological risk evaluation involves the following elements: 1) Presence and quality of source rock and potential for charge, 2) Presence and quality of reservoir interval, 3) Trap configuration and 4) Presence of seal and its integrity since hydrocarbon charge.

As mentioned above, only the Reindalspasset and Kapp Laila wells were drilled on the basis of sparse 2D seismic data. Seeps and oil-stained successions were well known in Svalbard (Abay et al., 2017), and after all, *"you find oil where you find oil"*. Onshore gas seeps are, for instance, considered to be part of the reason motivating NPN's drilling at Berzeliusdalen (Nils Martin Hanken, pers. comm., 2019). The remaining wells were drilled on the basis of geological reconnaissance work. Large oil companies that drilled in the 1970s like Fina, Total and Caltex, were all majors at that time and have certainly obtained existing data, as highlighted also in the thorough preparation by Caltex for the initial claiming in the 1960s (Brugmans, 2008). Caltex' claim applications, for instance, were based on geological knowledge available from Svalbard at that time including publications, aerial photography and limited seismic data. These were developed by professional geologists with competence from other petroleum provinces where Caltex operated. The smaller NPN sought professional geological competence early on, with strong co-operation with the Spitsbergen expeditions organised by Brian Harland's group at the University of Cambridge, and active use of competence from British Petroleum (BP) who owned some NPN shares in the 1960s. The main breakthrough of petroleum geological and geophysical research in Svalbard occurred in the early 1970s initiated foremost by the Norwegian oil company Statoil (now Equinor), followed by Saga Petroleum, Norsk Hydro and the Norwegian Oil Directorate. The activity had certainly an agenda also for preparation for the planned exploration in the Barents Sea. These studies were primarily led by David Worsley (University in Oslo) and Ron Steel (University in Bergen) and were mainly sponsored by Statoil. New geophysical methods, such as the snow-streamer (Eiken et al., 1989), were also developed during this phase. Potential source and reservoirs and tectonic development were reported and summarised in Steel & Worsley (1984). Furthermore, large major oil companies, like Fina, Total, BP, Agip and Caltex, conducted petroleum geological research at that time and for certain must have obtained some of this vital data for exploration of the frontier Svalbard area. Agip acquired near-shore seismic in Storfjorden 1971 within Svalbard's territorial waters, while NPN conducted onshore seismic refraction experiments in preparation of the Sarstangen drilling. Apart from these efforts, seismic acquisition in Svalbard was sparse in the 1970s.

Most of the oil companies in the 1960s and 1970s did not have much data on potential source and reservoir rocks for the Carboniferous, Permian and Mesozoic successions, but from regional correlations the risk of source and reservoir presence was likely considered as moderate or low. Oil-prone Lower Carboniferous coal deposits are present in the Billefjorden area (van Koevarden et al., 2011). Interbedded organic-rich mudstones in the Upper Carboniferous and Permian carbonates and evaporites occur in central Spitsbergen

(Nicolaisen et al., 2019). Porous Upper Carboniferous sandstone is also present in the Billefjorden area and especially in Nordaustlandet. Previous deep burial and enhanced paleo-temperatures, related to the development of the WSFB and the opening of the North Atlantic spreading axes in the west (Marshall et al., 2015b), contribute to this pervasive west–east trend for the sandstones and the organic-rich mudstones (i.e., following the principle of chemical compaction and maturation of source rocks; Bjørlykke, 2015; Bjørlykke & Jahren, 2015). The prediction of the reservoir properties of Upper Palaeozoic carbonates and spiculites is, however, challenging, due to the pervasive heterogeneity of the succession (Ehrenberg et al., 2001; Eliassen & Talbot, 2005; Stemmerik & Worsley, 2005).

In the Mesozoic, the Middle Triassic and Upper Jurassic source rocks, the Botneheia Formation and the Agardhfjellet Formation, respectively, the source potential varies from overmature (i.e., burned out) in westernmost and southwestern Spitsbergen to gas-prone in central Spitsbergen and progressively within the oil maturation window in east Spitsbergen and Edgeøya (Mørk & Bjorøy, 1984; Hvoslef et al., 1986; Brekke et al., 2014; Koevoets et al., 2016, 2018) and probably in Hopen. On Kong Karls Land, the Oxfordian organic-rich marine mudstone of the Agardhfjellet Formation is likely immature (Olaussen et al., 2018), as is the Middle Triassic Botneheia Formation on the entire Kong Karls Land Platform (Henriksen et al., 2011). The same trend is also followed for the reservoir properties of Mesozoic sandstones, i.e., tight, partly metasedimentary rocks, in southwestern Spitsbergen with poor to moderate porosity in central Spitsbergen to unconsolidated sandstone (i.e., Lower Cretaceous and Jurassic sands) in Kong Karls Land.

The Cenozoic was probably disregarded as it generally, at that time, was seen a coal-bearing succession with no sufficiently porous reservoir rocks. The lack of regionally significant sealing units capable of maintaining hydrocarbons through the severe Cenozoic tectonic and uplift episodes further contributed to an enhanced geological risk.

As for economic evaluations, we can only speculate on how the companies defined the net present value (NPV). A positive expected net present value (ENPV) can be calculated for the Reindalen prospect, based on the large structural closure and acknowledging a high reservoir quality risk. Such prospects are referred to as high-risk/high-reward. Without high-resolution seismic mapping, the delineation of structural closures in a foreland basin with heavily folded strata and thrust sheets in west and central Spitsbergen and gently folded sag/epicontinental basins in the east was very difficult. Why these companies decided to bypass acquisition of onshore seismic data as a basis for prospect definition can only be speculated, but may have been cost-related.

Norsk Hydro's Reindalspasset well culminated from the dedicated prospect mapping using 2D seismic in central Spitsbergen and successfully drilled a Carboniferous structure. But the negative result of the well, being no commercial discovery, suggests that further exploration in Svalbard will be very high risk. The strict environmental laws on Svalbard would also likely stop, or at least significantly hamper, any commercial exploitation activity at present. Already during the petroleum and coal mining activity comprehensive surveys of, for instance, vehicle tracks (Råheim, 1992) or the effect of seismic acquisition on Svalbard fauna (Prestrud & Øritsland, 1987) were developed. Localised contamination at the drill sites through, for instance, disposal of chemicals, drill cuttings or leakage of fuel, is considered likely though poorly documented site-specifically (Granberg et al., 2017). It is notable that petroleum exploration typically only involved giving a notice of the drilling operation, whereas the much stricter Svalbard Environmental Protection Act of 2002 requires comprehensive environmental assessments and specifically prohibits such activity in protected areas.

Some drilling in Svalbard might also have had a scientific agenda to study Svalbard's subsurface in context to future exploration in the Barents Sea – where the first exploration licences were only awarded in 1980. The Soviet boreholes at Vassdalen were considered primarily stratigraphic boreholes for facilitating geophysical interpretation, with testing of the petroleum potential a sub-objective (Bro, 1990a). Furthermore, the early explorers in Svalbard certainly gained experience in operating in a harsh Arctic climate.

With respect to development plans, little is documented on how eventual petroleum discoveries would be produced, processed and exported to markets. An exception is the Kapp Laila project, where development plans including a road and pipeline connection to Longyearbyen, an onshore processing facility and a quay, have been concretised (SNSK/Hydro, 1986). NPN were also involved in a project to design and construct an oil tanker capable of exporting oil from the circum-Arctic petroleum provinces, including Svalbard.

Conclusions

Svalbard is geologically an integral part of the Barents Shelf and thus an important window to decipher the stratigraphic evolution of this hydrocarbon province. Today this is as important as ever, with annual drilling campaigns increasingly targeting prospects and play models closer and closer to Svalbard. The northern Barents Shelf is currently closed for petroleum exploration, though increasingly more geological information is available from this frontier province. The Norwegian authori-

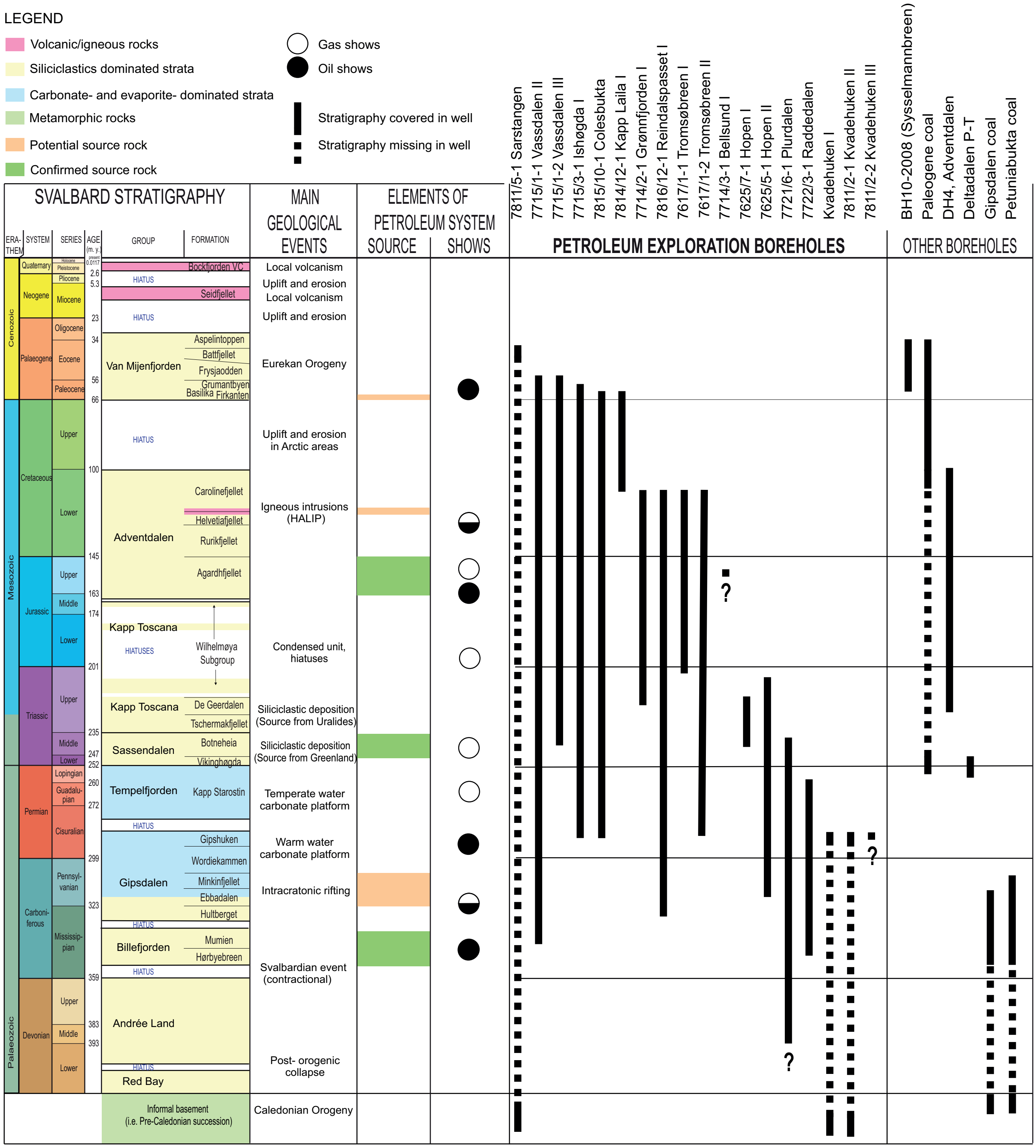

Figure 13. Simplified stratigraphic column of Svalbard illustrating the stratigraphic position of the exploration boreholes. The stratigraphic column is based on Dallmann (2015a).

ties conclude that the area contains a significant amount of yet-to-find resources, with a mean of 1370 mill. Sm^3 of oil equivalents (NPD, 2017). What is politically interesting is whether any of these potential resources will ever be targeted by commercial drilling – both the fragile Arctic ecosystems at risk from oil exploration this far north, and the question on whether this part of the continental shelf belongs to Norway or solely Svalbard as discussed previously are worth keeping in mind.

What is often overlooked, however, is that oil exploration in Norway actually started in Svalbard, a decade before the Norwegian authorities even contemplated the presence of hydrocarbons on the Norwegian Continental Shelf, and that the exploration rights were almost given away for free to foreign companies. Seeps and oil-stained outcrops were reported even before the Svalbard Treaty was signed in 1920. A relatively intense exploration activity resulted in the drilling of eighteen petroleum exploration wells from 1961 to 1994, none of which encountered commercial quantities of hydrocarbons. Reduced reservoir quality (commonly being too tightly cemented), limited structuring (lack of traps and/or proper seal) and leakage following Cenozoic uplift have been identified as the main exploration risks.

The past 20 years have been characterised by increased environmental protection of Svalbard's unique landscape, drastically reducing the area available for commercial exploitation of natural resources. Research and coal exploration drilling, however, indicates the presence of moveable hydrocarbons in the vicinity of Svalbard's settlements. The blow-out near Pyramiden also raises an important question of environmental concerns – pointing to the potential hazardous effect on Svalbard's nature from petroleum exploitations. Drilling in Svalbard for research purposes, on the other hand, with the Longyearbyen CO_2 lab, the Sysselmannbreen borehole or the recent Permian–Triassic Deltadalen campaign, can be executed at low environmental risk. Such campaigns are important for the scientific understanding of Svalbard's geological record. A dedicated and targeted shallow stratigraphic drilling campaign with comprehensive coring, logging and an associated analytical programme would certainly aid in deciphering both Svalbard's geological evolution as well as global climatic evolution at geological time scales. For a start, a closer look at the 29 km of the cumulative stratigraphy penetrated by the petroleum exploration wells is required to further understand the petroleum system elements of the northern Barents Shelf (Fig. 13).

We can conclude that several phases of conventional petroleum exploration onshore Svalbard have been conducted, with no discoveries and with no remaining petroleum claims on the islands at the present time. But given Svalbard's geopolitical significance during the Cold War, it was by some seen as a relief that no commercial hydrocarbon accumulations were found. To quote Norway's foreign minister during the 1970s and 1980s, Knut Frydenlund, *"Had the petroleum investigations by the international companies in the 1960s provided results, the situation on Svalbard could have become extremely difficult. It could have become an oil race that would, at that time, have caused Norway problems."*

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