Hammerfest Basin Composite Tectono-Sedimentary Element, Barents Sea

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Abstract: The Hammerfest Basin is an east–west-trending graben located between the Loppa High and the Finnmark Platform in the southern part of the Norwegian Barents Sea. Mainly siliciclastic strata of Carboniferous–Cenozoic age cover the Caledonian basement and have a total estimated thickness of 5–8 km. The basin evolved through several tectonic phases: Carboniferous rifting, Late Jurassic rifting, opening of the Atlantic Ocean, Oligocene reorganization of plate movements and post-glacial isostatic rebound. An east–west-trending dome in the centre of the basin developed during the main extensional tectonic event in the Late Jurassic. Horst structures represent the main hydrocarbon traps. Erosional channels on the flanks of the basin represent entry points for Lower Cretaceous sands. For the rest of the Cretaceous and Cenozoic intervals, no significant reservoir sands are expected.

The first exploration well in the Barents Sea in 1980 was located in the Hammerfest Basin and by 2019 a total of 45 wells had been drilled in the basin, with 34 classified as exploration wells. The result is 18 oil and gas discoveries, which gives a discovery rate of 53%. Two fields are now in production: the Snøhvit gas-condensate fields and the Goliat oilfield.

A total of 340 Msm^3 (2140 Mbbl) recoverable oil equivalents have been discovered. For the middle Jurassic play, the yet-to-find potential may be around 50 Msm^3, distributed in several small structures in the basin. Following the oil discovery in the Middle Triassic interval in the Goliat structure, and because several of the previously drilled structures only penetrated the Jurassic and the uppermost Triassic section, considerable exploration potential may exist in the deeper Triassic interval in structures with the best reservoir facies. Stratigraphic traps of Cretaceous age may have a moderate petroleum potential, with excellent reservoirs encountered along the flank of the basin. Exploration potential may also exist in Upper Permian sandstones along the southern and eastern flanks of the basin. However, in large parts of the basin, the remaining potential is in the deep structures and, hence, is gas prone.

The east–west-trending Hammerfest Basin is a linear rift basin located in the Norwegian Barents Sea between the Loppa High and the Finnmark Platform (Fig. 1). Mainly siliciclastic rocks of Carboniferous–Cenozoic age form its sedimentary cover (Fig. 2). The basin's sedimentary infill is subdivided by several major unconformities into five individual TSEs, which resulted from major tectonic phases. Therefore, the Hammerfest Basin represents a Composite Tectono-Sedimentary Element (CTSE), in the context of other elements expressed in enclosures A-F.

The petroleum exploration in the Hammerfest Basin started in the 1960 and 1970s with acquisition of magnetic data (Åm 1975). Based on seismic mapping, the basin appeared as a faulted terrain with several horst and graben structures. Following acquisition of a large amount of seismic data together with several drilled wells, the geological evolution of the Hammerfest Basin was well documented in numerous papers (see the references in the 'Tectonic setting, boundaries, main tectonic, erosional and depositional phases' section).

The first exploration well in the Barents Sea, drilled in 1980, was located in the southwestern part of the Hammerfest Basin. So far, the exploration activity in the basin has resulted in two producing fields: Snøhvit gas-condensate fields (comprising the Askeladden, Albatross and Snøhvit discoveries) and the Goliat oilfield.

The east–west-trending Jurassic faults and half-graben represent the main petroleum exploration targets. All major discoveries are in Late Jurassic structures in sandstones of Middle–Late Triassic and Middle Jurassic age. Deeper Triassic reservoirs and Permian carbonates have recently become exploration targets, and shallower stratigraphic traps are likely targets at Lower Cretaceous level, with potential reservoir sands sourced from elevated areas around the basin.

The aim of this article is to describe the Hammerfest Basin as a 'Tectono-Sedimentary Element' (TSE) in context with other Arctic TSEs presented in this Memoir, and to address hydrocarbon potential that still may exist in the basin. The content, illustrated with maps, well logs and geoseismic profiles, intends to characterize the main tectonics events and sedimentary sequences in the basin. Description of the petroleum plays indicates considerable remaining hydrocarbon potential.

Age

Based on seismic and well data, and the regional geological context, the Hammerfest Basin CTSE is interpreted to consist of Early Carboniferous–Middle Eocene sediments.

Geographical location and dimension

The Hammerfest Basin is an elongated graben in the southwestern part of the Norwegian Barents Sea; it is 160 km long, 70 km wide and covers an area of 11 500 km^2 (Figs 1, 3 and 4; Enclosure A).

Principal datasets

Wells

By the end of 2019, 45 wells had been drilled in the Hammerfest Basin since the first well in 1980 (Fig. 4; Enclosure F). The greatest exploration activity was between 1980 and 1992 when 32 exploration wells were drilled, with Snøhvit in 1984 being the only significant discovery. An 8 year-period followed with no drilling in the Barents Sea, until the Goliat oil discovery in 2000. In the wake of this, 13 wells were drilled after 2005, with the latest in 2017 on the Jurassic Blåmann structure (well 7121/8-1) and in 2019 on the Cretaceous Pointer/Setter target (well 7121/1-2S).

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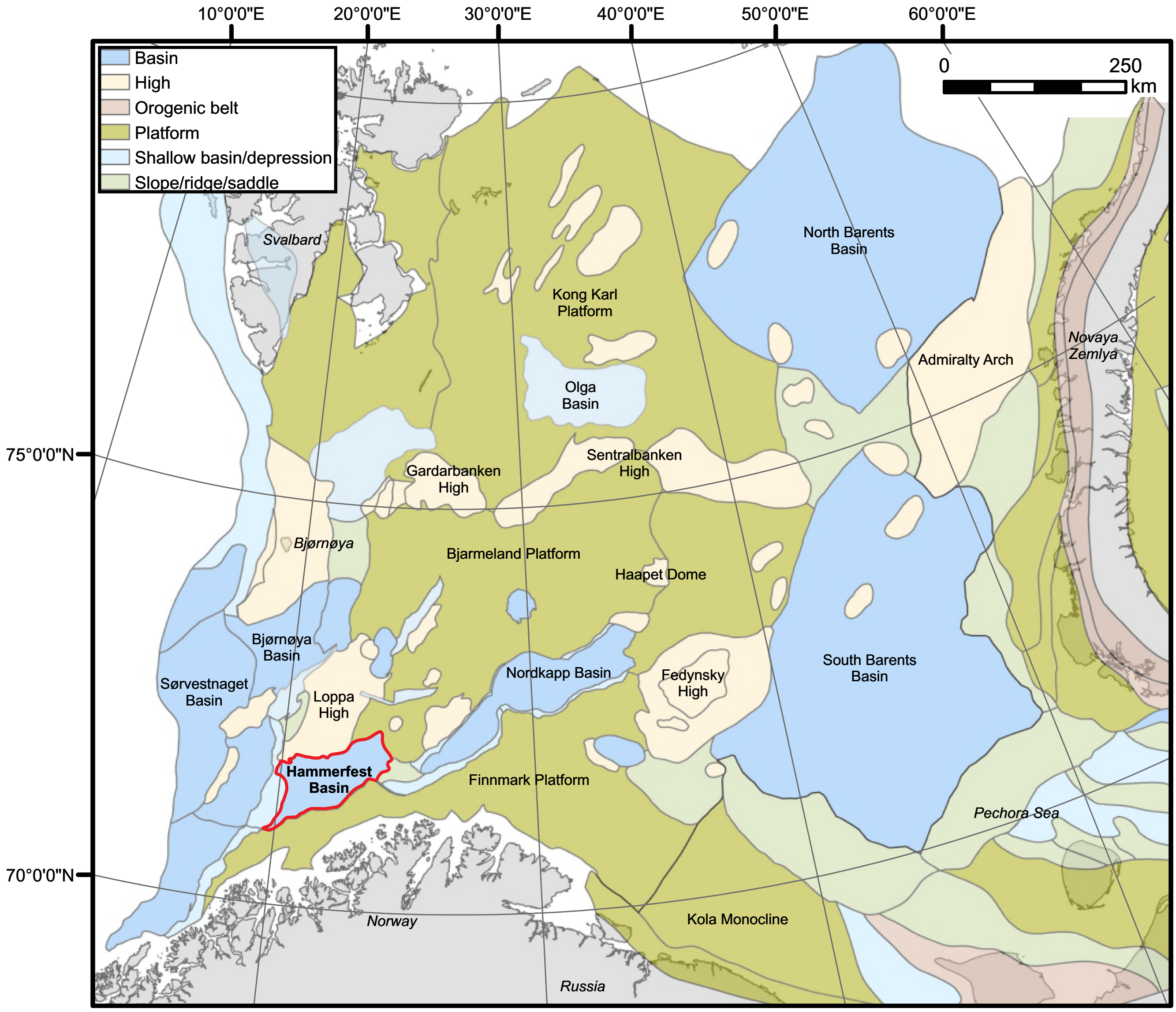

Fig. 1. Location and structural elements of the Barents Sea (modified from NPD 2017 https://www.npd.no/en/ and Henriksen *et al.* 2011*b*). The Hammerfest Basin CTSE is outlined in red.

All wells have a full suite of logs recorded, which includes gamma, density, resistivity and sonic. In addition, 37 wells have cores and 11 wells with discovered hydrocarbons were tested for fluid flow. The most complete cored well is 7119/12-2 with 220 m of continuous cores (together with well 7128/6-1, one of the longest cored intervals in the Norwegian Barents shelf). Generally, the log and sample data are of very good quality.

Seismic and other geophysical data

The Hammerfest Basin is the most explored part of the Barents Sea, and the seismic data coverage is very dense, with 3D seismic data covering the entire basin (Fig. 4), of which large parts have open access through the Norwegian Petroleum Directorate (NPD) website and the Diskos National Database (http://www.npd.no). Several of the 2D and 3D datasets are from early exploration activity in the basin (between 1980 and 1992), but the quality of these data vintages is still moderate to very good. The hard seabed, near-surface pockmarks and iceberg scours, which cause complex multiples and diffractions, are challenges for the data quality in parts of the basin. The recent acquisition of broadband seismic data and better source–receiver positioning systems, together with enhanced processing, have mitigated these problems. A large part of the basin is also covered by modern controlled source electromagnetic (CSEM) data. Finally, gravity and aeromagnetic data exist over the entire basin (Smelror *et al.* 2009; Gaina *et al.* 2011; Sandwell *et al.* 2014).

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

The general geological evolution of the western Barents Sea, including the Hammerfest Basin, is well documented in numerous papers (Øvrebø and Talleraas 1977; Gloppen and Westre 1982; Rønnevik *et al.* 1982; Faleide *et al.* 1984; Gabrielsen *et al.* 1984, 1990; Olaussen *et al.* 1984; Rønnevik and Jacobsen 1984; Spencer *et al.* 1984, 2011; Gjelberg *et al.* 1987; Johannesen and Embry 1989; Skagen 1993; Lundin and Doré 1997; Gudlaugsson *et al.* 1998; Larssen *et al.* 2002; Brekke *et al.* 2001; Cocks and Torsvik 2005; Seldal 2005; Cavanagh *et al.* 2006*a*, *b*; Worsley 2008; Ohm *et al.* 2008; Riis *et al.* 2008; Worsley 2008; Smelror *et al.* 2009;

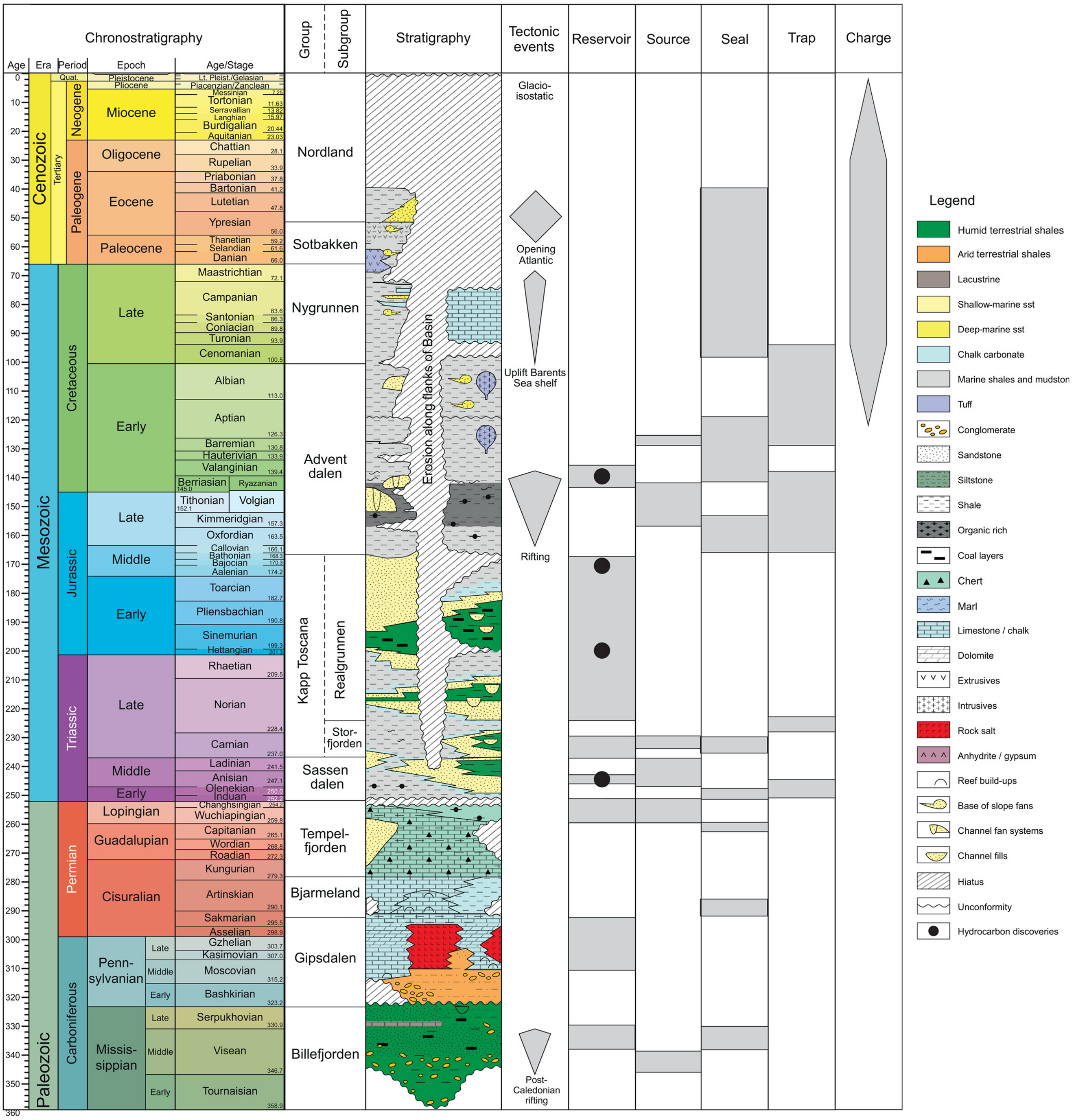

Fig. 2. Stratigraphic column and event chart of the Barents Sea based on Gabrielsen *et al.* (1990) and Cohen *et al.* (2016). The figure shows large scale changes in depositional environment at the Permian–Triassic and Jurassic–Cretaceous boundaries. The upper part of sedimentary cover is absent due to a drastic recent post-glacial uplift and associated erosion.

Henriksen *et al.* 2011*a*, *b*, 2018; Duran *et al.* 2013; Lerch *et al.* 2016; Marín *et al.* 2018). Several post-Caledonian tectonic phases have influenced the present-day tectonic grain of the shelf (e.g. Rønnevik *et al.* 1982; Ziegler 1988; Faleide *et al.* 1988, 2008; Gudlaugsson *et al.* 1998).

The Hammerfest Basin is a relatively shallow graben located between the Loppa High, the Finnmark Platform and the deeper Tromsø Basin (Figs 5–7). The basin is fault controlled, and was probably established in the Early–Middle Carboniferous (Visean–Bashkirian) (Rønnevik *et al.* 1982; Rønnevik and Jacobsen 1984; Gabrielsen *et al.* 1990; Gudlaugsson *et al.* 1998; Elvebakk *et al.* 2002). The borders of the basin are delimited by the Troms Finnmark Fault Complex to the south, the Asterias Fault Complex to the north and the Ringvassøy Loppa Fault Complex to the west (Figs 3 and 5). The basin is clearly separated from the surrounding highs in the gravimetric data (Enclosure C), whereas the transition towards the Bjarmeland Platform to the east is more gradual, with only minor change of the negative gravimetric anomaly. Caledonian metamorphic rocks of assumed Silurian–Devonian age represent the acoustic basement with overlying sediments of Carboniferous (Visean) and Permian age. The western part of the basin is characterized by a central dome located along the basin axis and by an east- to ESE-trending system of internal faults (Fig. 5). All these features formed during Late Jurassic–Early Cretaceous tectonism

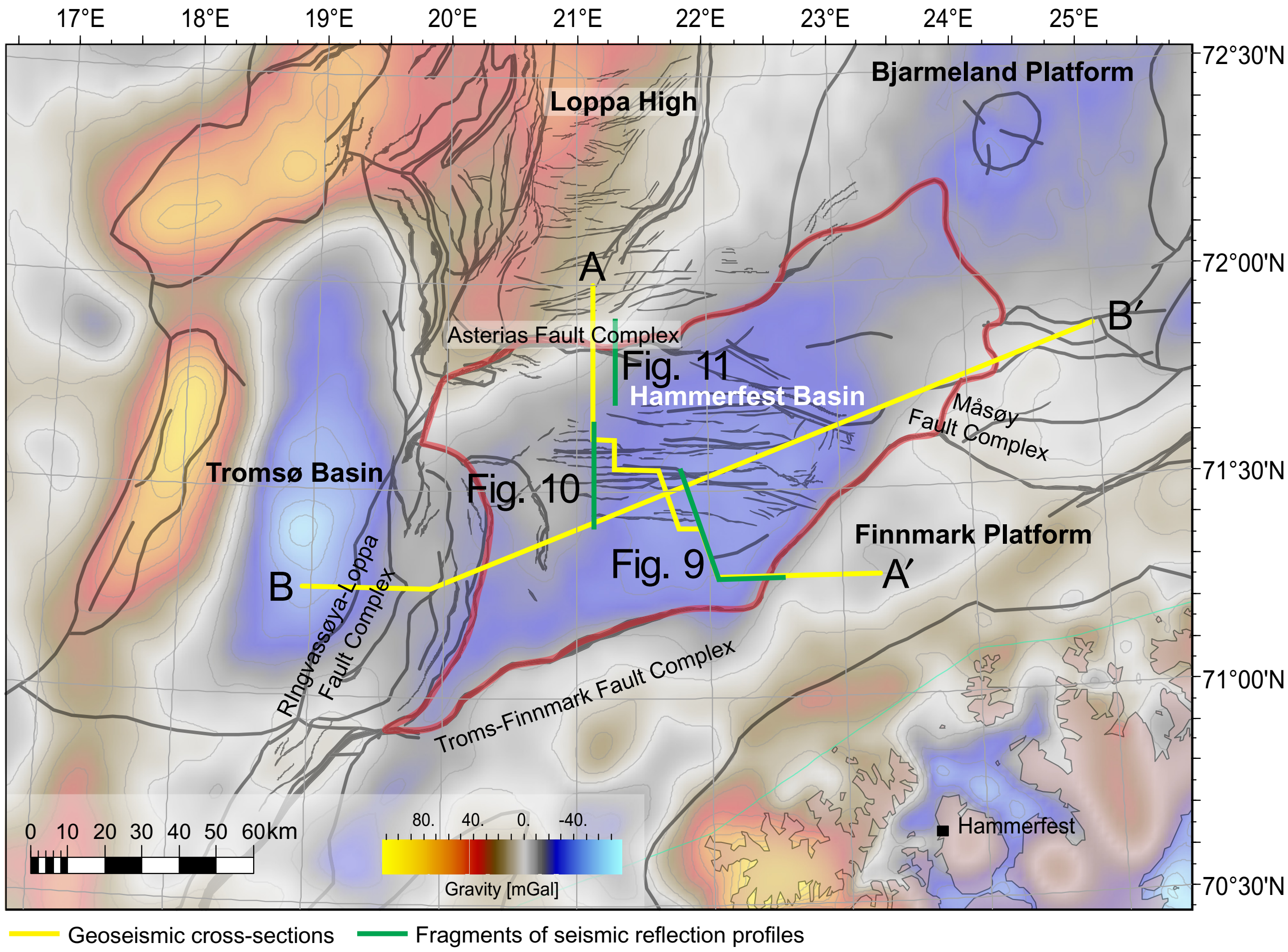

Fig. 3. Free-air gravity anomaly for the Hammerfest Basin based on satellite altimetry (Sandwell *et al.* 2014). Structural elements and fault patterns are shown, together with the location of the cross-sections given in Figures 6, 7, 9–11.

(Seldal 2005; Faleide *et al.* 2008). The eastern part of the Hammerfest Basin is generally less influenced by faulting and has been described as a sag basin (Gabrielsen *et al.* 1990).

The Caledonian Orogeny forms the basement of the Hammerfest Basin. In well 7120/12-2, a 70 m-zone of weathered rocks (arkoses) indicates a period with aerial exposure and weathering of the basement (Fig. 8). As speculated by Kjøde *et al.* (1978), Roberts (1996) and Gee *et al.* (2008, 2010), an indication of WNW-trending faults exists in the eastern part of the basin (i.e. the Måsøy Fault Complex: Fig. 5), probably representing reactivated Neoproterozoic Timanian basement fabrics.

Five major post-Caledonian tectonic events have affected the southwestern Barents Shelf including the Hammerfest Basin (e.g. Rønnevik *et al.* 1982; Ziegler 1988; Gudlaugsson *et al.* 1998; Faleide *et al.* 2008) (Fig. 2):

1. Lower–Middle Carboniferous rifting (Visean–Bashkirian);
2. Late Jurassic initiation of rifting;
3. Lower Cretaceous reactivation, growth fault and footwall uplift;
4. Early Eocene opening of the Atlantic Ocean;
5. Oligocene–Miocene transform movements in the Atlantic Ocean; and
6. Plio/Pleistocene glacio-isostatic uplift and erosion.

Corresponding sedimentary accumulations form the following individual TSEs:

1. Lower–Middle Carboniferous synrift TSE;
2. Permian–Jurassic post-rift sag TSE;
3. Upper Jurassic–Lower Cretaceous (Neocomian) synrift TSE;
4. Aptian–Albian post-rift TSE; and
5. Cenozoic shelf terrace TSE.

Therefore, the Hammerfest Basin represents a vertical stack of the five individual TSEs, which together constitute a composite TSE.

During the Late Paleozoic, the area of the future Norwegian Barents Sea shelf was located at the centre of the Euramerica supercontinent where a large NNE-trending rift system developed during the Lower–Middle Carboniferous extensional episode (e.g. Rønnevik *et al.* 1982; Faleide *et al.* 1984, 2008; Gudlaugsson *et al.* 1987, 1998; Gabrielsen *et al.* 1990). Sediment deposition took place in a complex of rapidly subsiding basins between more stable platforms. Following the initial rift in the Visean, more intense rifting and subsidence continued during the Middle Carboniferous until the Bashkirian (Ehrenberg *et al.* 1998, 2000; Henriksen *et al.* 2021). This led to fault-controlled subsidence, and the formation of depocentres along the rift axis, filled with thick Paleozoic sediments (Figs 3, 6 and 7). Well 7120/12-2, drilled at the southern flank of the basin in 1981, proved almost 1000 m of Permian sediments over a weathered basement (Fig. 8). Continuous reflectors in the Permian and Triassic sequences indicate quiet tectonic conditions with deposition of stratified sedimentary succession in the gentle subsiding basin (Fig. 9).

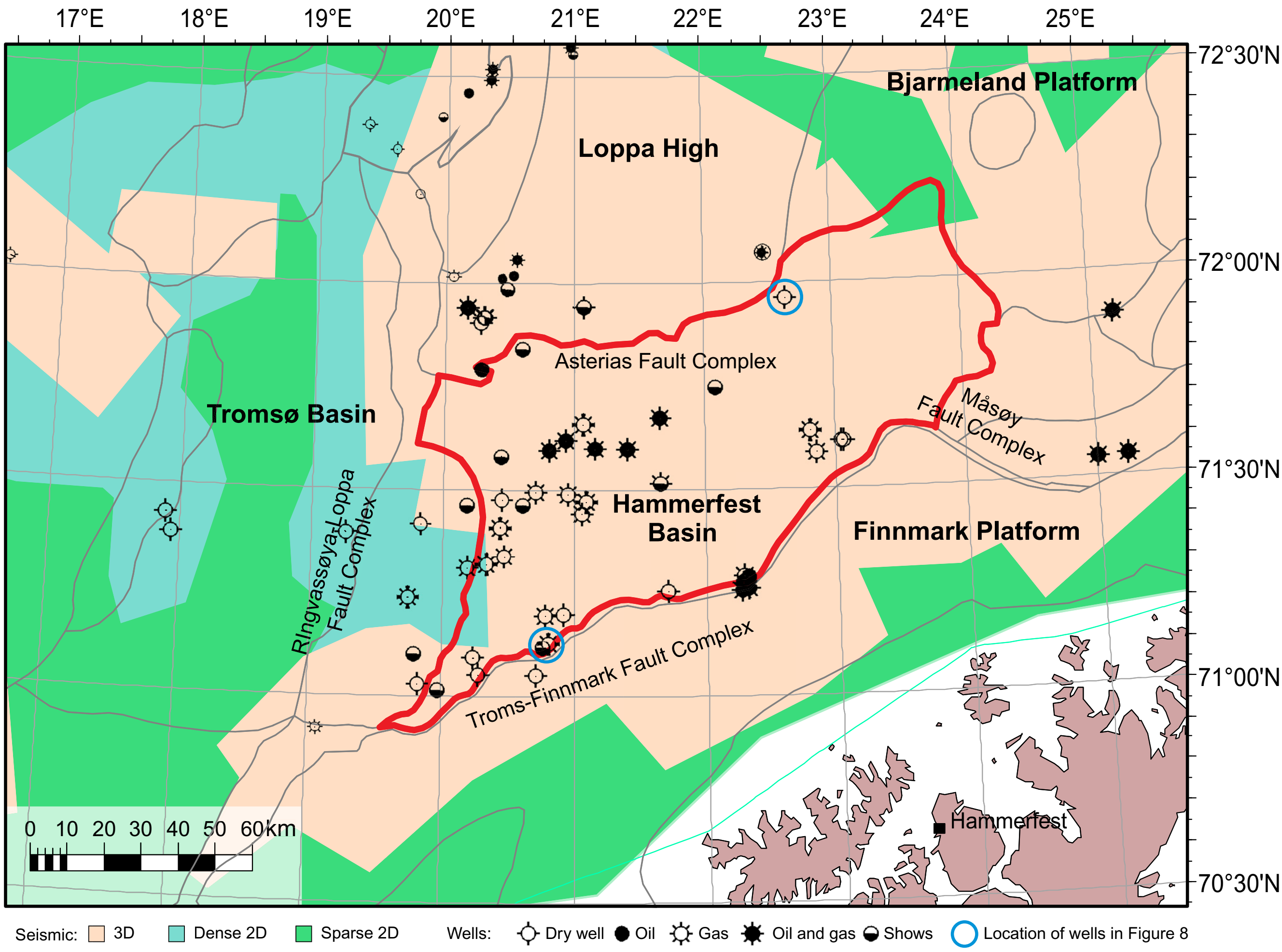

Fig. 4. Seismic and well data coverage in the Hammerfest Basin. Location of wells in Figure 8 marked with blue circles.

The transition from carbonate to clastic deposition occurred in the late Permian as a result of the northward drift of Pangaea causing a climate change (Larssen *et al.* 2002). In addition, the Uralian Orogeny provided a source area for the vast quantities of clastic material sourced from the east. The Mesozoic package in the southwestern Barents Sea was deposited in a shallow epicontinental seaway with a general northwesterly progradation (Glørstad-Clark *et al.* 2010, 2011; Klausen *et al.* 2015). The thickness of the Triassic sequence in the basin increases from south to north. The Permian and Triassic sections stretch continuously over the present-day Loppa High area, which at that time was part of a larger regional depositional basin (Figs 5 and 9). The main provenance area for the sediments was to the SE (Uralian Mountains), but locally, on the Finnmark Platform and in the Hammerfest Basin, sediments were also sourced from the Fennoscandian Shield. General westward sediment progradation, caused by a regional regression, prevailed during the Late Triassic and Early Jurassic (e.g. Mørk 1999; Smelror *et al.* 2009; Glørstad-Clark *et al.* 2010, 2011; Henriksen *et al.* 2011*b*; Høy and Lundschien 2011; Lundschien *et al.* 2014; Klausen *et al.* 2015). The related migration of the shoreline provided the main reservoir in the Hammerfest Basin. In Late Jurassic–Early Cretaceous time, major rifting took place (Fig. 10) forming the present-day outline of the CTSE. In the interior of the basin, east–west-trending horst and graben structures developed (e.g. Rønnevik *et al.* 1982; Spencer *et al.* 1984; Berglund *et al.* 1986; Sund *et al.* 1986; Gabrielsen *et al.* 1990; Seldal 2005; Faleide *et al.* 2008).

Tectonic reactivation along the Troms Finnmark Platform and the Asterias Fault Complex took place in Early Cretaceous time. Major canyons developed on the elevated Loppa High and the Finnmark Platform, representing entry points for Lower Cretaceous sand transported into the Hammerfest Basin (Fig. 11).

The rifting and opening of the Atlantic Ocean in the Paleocene–Eocene caused transport of sediments to the subsiding basin from uplifted areas, as indicated from seismic data showing progradation from north to south (Fig. 9).

Another transpressive fault reactivation in the Hammerfest Basin took place in early Oligocene time due to plate-boundary reorganization along the Atlantic Margin. The Oligocene event probably represented an important pre-glacial phase of regional uplift. Clear evidence for this tectonic event is seen along the western Barents Sea margin (Doré and Lundin 1996; Faleide *et al.* 1988) and on the western Svalbard (e.g. Harland 1969; Eldholm *et al.* 1984, 1987).

Significant post-glacial uplifts affected the whole Barents Sea region in Plio-Pleistocene time, resulting in *c.* 1000–1700 m of uplift in the Hammerfest Basin area and erosional removal of 1000–1500 m of Cretaceous–Tertiary sediments (Richardsen *et al.* 1991; Vorren *et al.* 1991; Nyland *et al.* 1992; Augustson 1993; Doré and Jensen 1996; Riis 1996; Doré *et al.* 2002; Cavanagh *et al.* 2006*a*, *b*; Andreassen *et al.* 2008; Knies *et al.* 2009; Laberg *et al.* 2010, 2012; Henriksen *et al.* 2011*a*; Zieba and Grøver 2016; Ktenas *et al.* 2017). The thickness of the Tertiary units (Paleocene–Eocene) exceeds 500 m in some places.

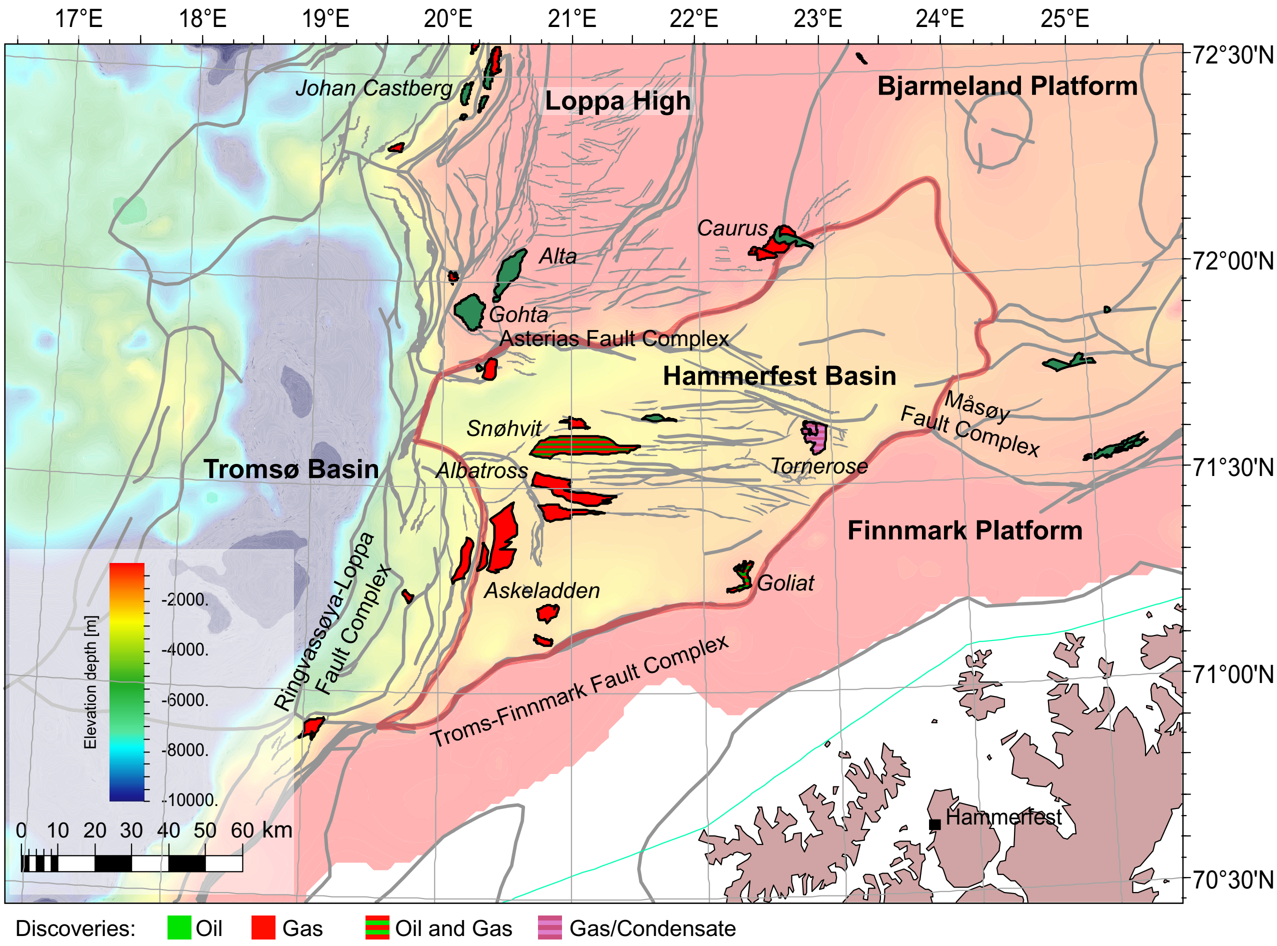

Fig. 5. Base Cretaceous Unconformity depth map showing location of hydrocarbon discoveries.

Underlying and overlying rock assemblages

Age of underlying basement or youngest underlying sedimentary unit

Deformed gneiss encountered in the well 7122/12-2 support the presence of the Caledonian basement beneath the Hammerfest Basin (Enclosure D). However, the exact age of the basement is uncertain. Traditionally, it is believed that the Scandian Caledonides were affected by two major tectonic phases: (1) the Finnmarkian phase (Cambrian–Ordovician); and (2) the Scandian phase (Silurian–Devonian). The western Barents Sea areas, like the Hammerfest Basin, were most influenced by the latter (Smelror *et al.* 2009; Klitzke *et al.* 2015).

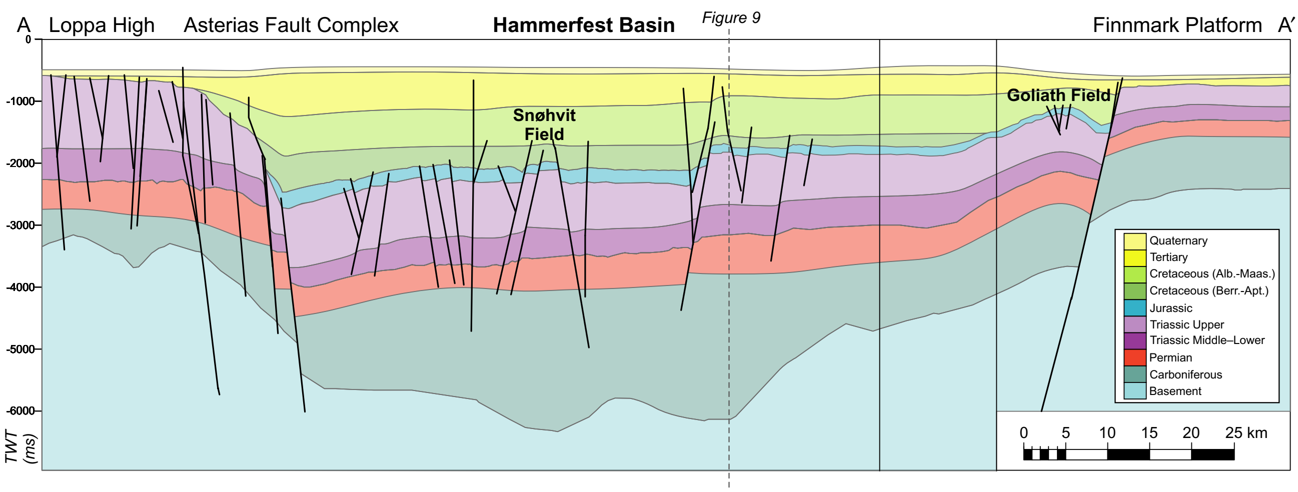

Fig. 6. Regional geoseismic profile A-A′ showing the stratigraphy of the Hammerfest Basin CTSE, orthogonal to the basin axis. The location is given in Figure 3.

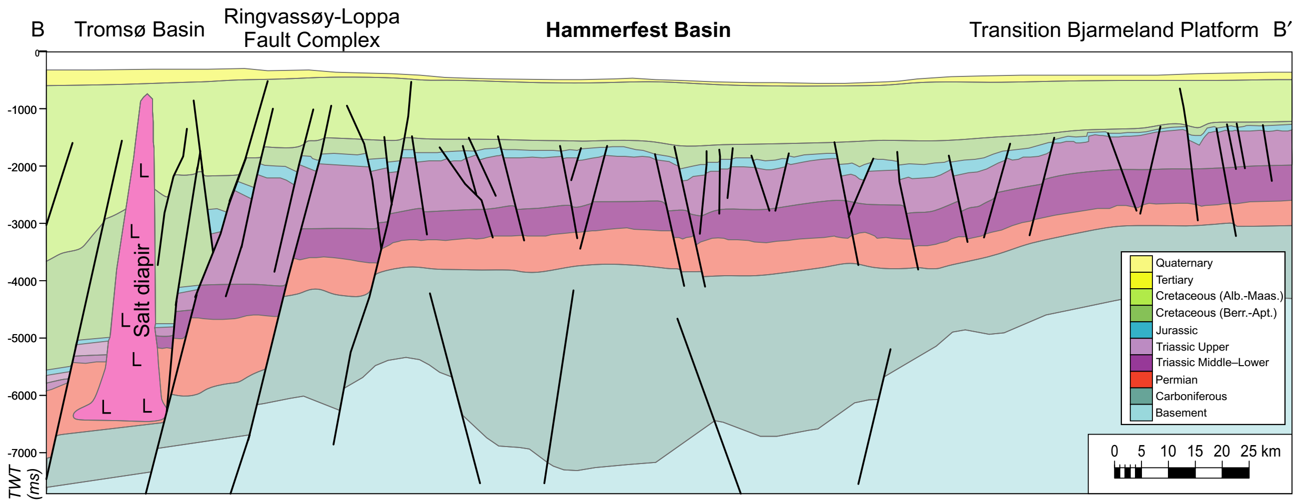

Fig. 7. Regional geoseismic profile B–B′ parallel to the basin axis. The location is given in Figure 3.

Age of oldest overlying sedimentary unit

The Plio-Pleistocene sediments are considered the oldest overlying unit of the Hammerfest Basin CTSE. The thickness of the unit ranges from a few metres to around 150 m.

Subdivision and internal structure

Numerous east–west-running extensional faults define internal structures in the basin, which have been described by several authors (e.g. Øvrebø and Talleraas 1977; Rønnevik *et al.*

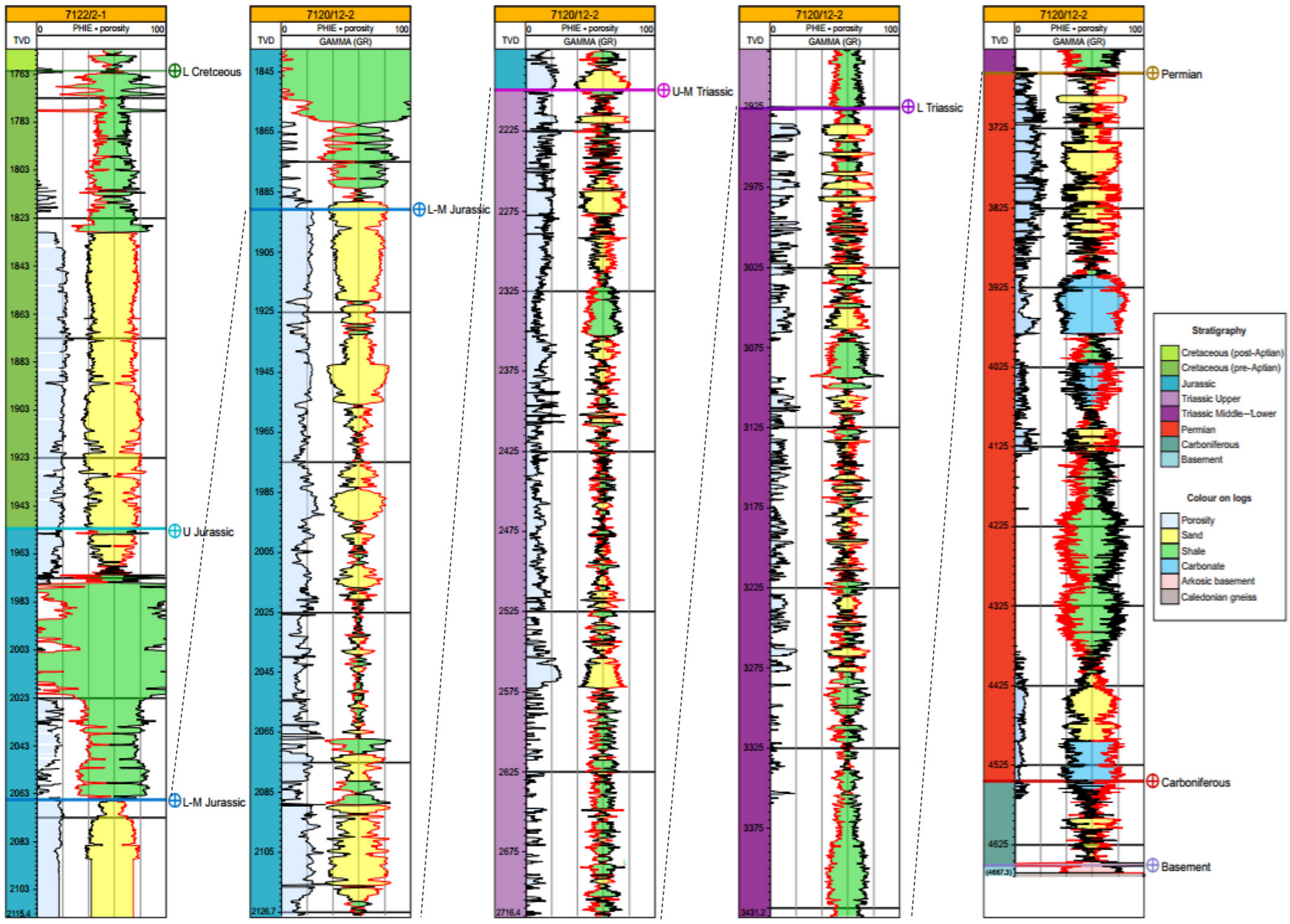

Fig. 8. Well logs showing the penetrated stratigraphic columns with examples of different reservoir units within the Hammerfest Basin. The log panels represent reservoir zones in (from left to right) the Lower Cretaceous, Lower Jurassic, Upper Triassic, Lower Triassic and Paleozoic. The first log panel is from well 7122/2-1, the others from well 7120/12-2. For the location see Figure 4. The gamma log (black) is plotted with a reverse gamma (red) with a colour flip when they cross. The scale on top refers to the porosity log along the left-hand side of the well panels.

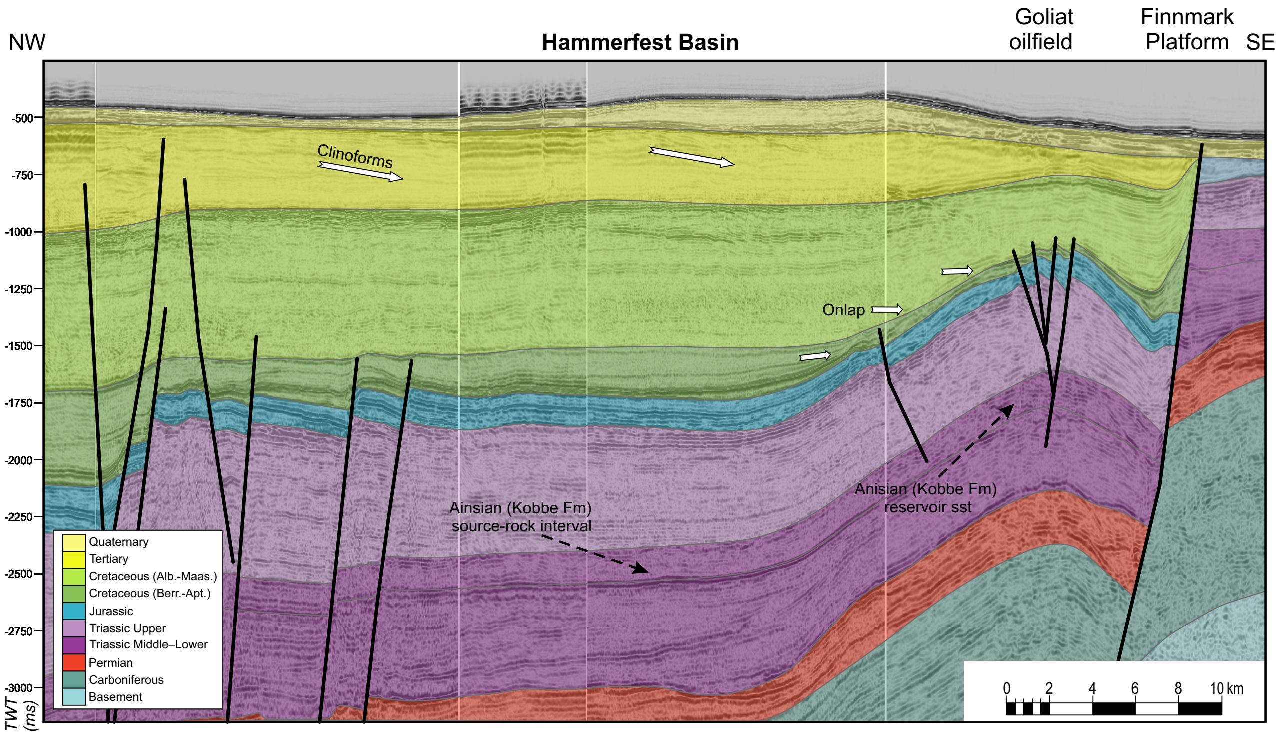

Fig. 9. Geoseismic profile. For the location, see Figure 3. The profile shows the southern flank and the central part of the dome structure and includes the Goliat oilfield. Arrows indicate Cretaceous onlap and Tertiary progradation.

1982; Gabrielsen *et al.* 1990; Seldal 2005; Henriksen *et al.* 2018). Large listric faults and rollover structures, where the Goliat oilfield is located, are documented along the southern flank of the basin (Fig. 9). Downfaulted in the SW direction, NNE–SSW-striking structures, the Ringvassøy Loppa Fault Complex, represent terraces in the transition to the Tromsø Basin (Fig. 5). A central axial zone of the basin is represented by an east–west-trending faulted dome, which hosts the Snøhvit and Albatross fields (Figs 5 and 10). Several horst and half-graben segments, 10–20 km long and 2–5 km wide, exist in the central basin. The central high rose up because of extensional and probably some transpressional movement (Mohammedyasin *et al.* 2016) during the Upper Jurassic–Lower Cretaceous. The tectonic activity developed minor separate basins on the northern and the southern flanks of the Hammerfest Basin, which created accommodation space for the synrift and post-rift sediments (Figs 6 and 11). A dramatic increase in thickness of the Lower Cretaceous sediment package is seen in the Tromsø Basin towards the west (Fig. 7). In the eastern part of the basin, NW–SE-trending faults may indicate an extension of the Måsøy Fault Complex into the basin (Figs 3 and 5). This fault trend may be inherited from the

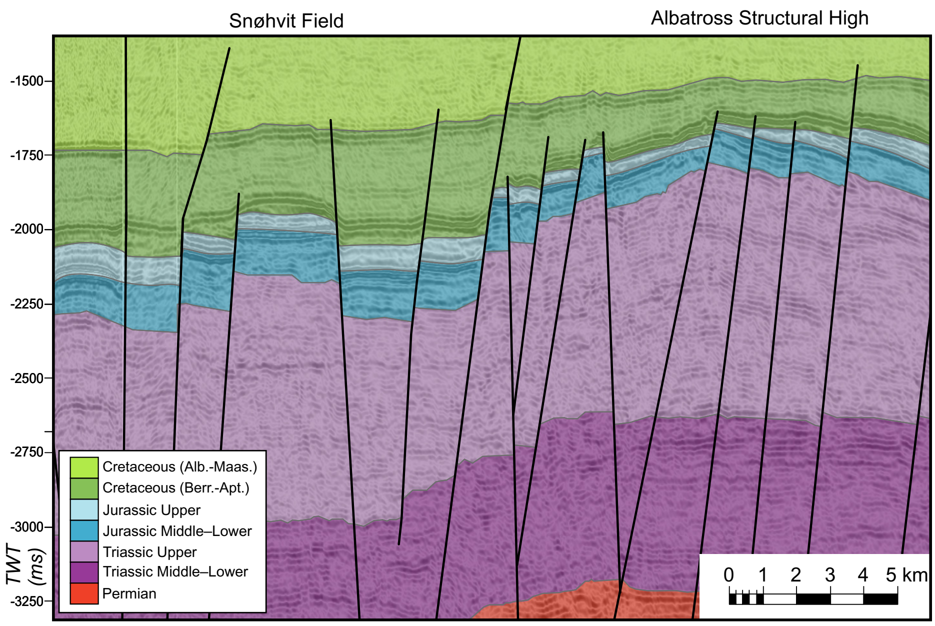

Fig. 10. Geoseismic profile. For the location, see Figure 3. The profile is orthogonal to the Snøhvit and Albatross gas discoveries within the central part of the Hammerfest Basin.

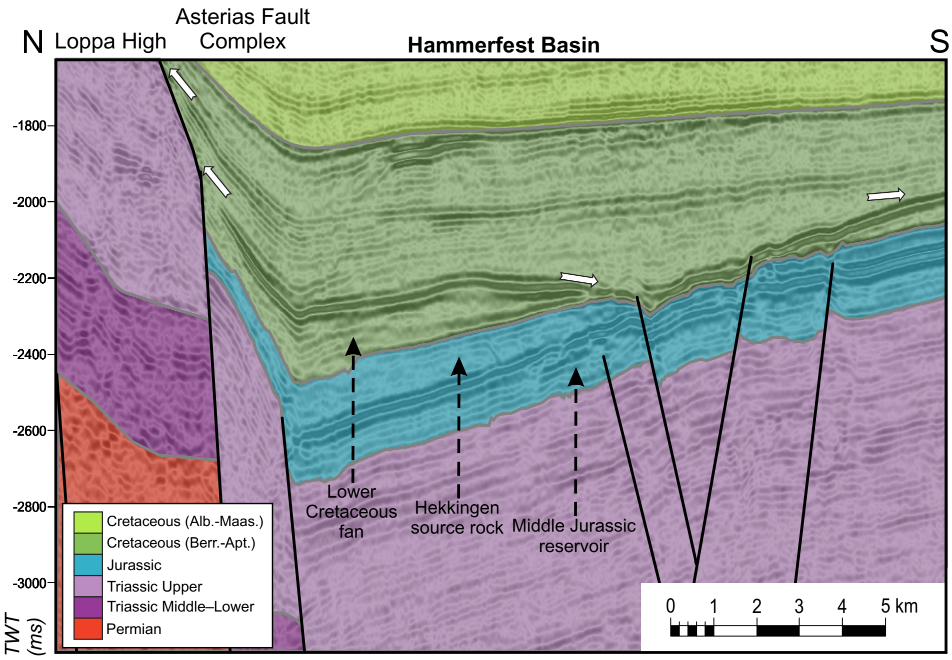

Fig. 11. Geoseismic profile. For the location, see Figure 3. The profile shows the northern flank of the basin and an example of Upper Jurassic–Lower Cretaceous gravity flows. White arrows indicate Cretaceous onlap.

old Timanide trend and an extension of the Trollfjord Komagelv Fault Complex (TKFC) on Varanger island further to the east (Henriksen *et al.* 2021).

Sedimentary fill

Total thickness

Hammerfest Basin is a relatively shallow basin. The total present-day sediment thickness proved to be 4650 m in well 7120/12-2. Regional depth to basement estimates (Skilbrei 1991; Smelror *et al.* 2009 and references therein) indicate general sediment thicknesses of around 5–8 km, with the thickest part in the centre of the basin (Fig. 6).

Lithostratigraphy/seismic stratigraphy

Figure 2 illustrates the stratigraphic column of the Hammerfest Basin and surrounding areas. Deep well 7120/12-2 provides valuable information about the stratigraphy of the entire basin's sedimentary infill down to the metamorphic basement (Fig. 8).

At the base of the section, a 70 m-layer of arkoses of uncertain age developed as a result of the weathering of the top of the basement gneiss.

A basal carbonate unit of Permian age is resting on an unconformity probably of Carboniferous age. A thick silty and shaly sediment unit rests on the basal carbonate unit, marking a gradual change in lithology from carbonate to shale, silt and sand (Fig. 8, 4490–4075 m). A change in depositional environment of the Permian section from siliciclastic sediments in the western part of the basin to carbonate build-ups probably interbedded with evaporites towards the NE (Henriksen *et al.* 2018) may be related to tectonic activity: that is, reactivation of the Måsøy Fault Complex (Fig. 5). A new episode of carbonate deposition took place probably in the Kazanian (Fig. 8, 4075 m). This interval has been described in Loppa High and Finnmark Platform wells, and in outcrops on Svalbard, and generally consists of bryozoan and brachiopods tightly cemented carbonates with a limited reservoir potential (Stemmerik *et al.* 1995; Stemmerik 1997). Well 7120/12-2 (Fig. 8) and the nearby well 7120/12-4 on the Finnmark Platform encountered a 200 m sandstone of moderate reservoir quality in the Upper Permian interval. This differs from what is observed in the eastern Finnmark Platform and on the Loppa High. However, on Svalbard, a similar sandstone occurrence in the Upper Permian is documented, and another example occurs in the Pechora Basin in the Russian part of the Barents Sea (Spencer *et al.* 2011 and references therein; Stoupakova *et al.* 2011). The provenance area for the siliciclastic Permian sediments in the Hammerfest Basin is most likely to be the Norwegian mainland.

The Triassic section consists of 1000–1500 m of alternating sandstones and shales (Figs 2 and 8). The depositional environment changes from marine at the Lower–Middle Triassic transition to terrestrial in the Upper Triassic (e.g. Riis *et al.* 2008; Smelror *et al.* 2009; Glørstad Clark 2010; Henriksen *et al.* 2011*b*; Høy and Lundschien 2011; Kaminsky *et al.* 2011; Lundschien *et al.* 2014; Klausen *et al.* 2015).

In seismic data, the marine part of the lower Triassic section is represented by continuous parallel to low angle reflectors of moderate amplitude indicating progradational systems of clinoforms. The Triassic source rock proven in the Goliat field is believed to be of Anisian age and is most likely an analogue to the Botnheia Formation on Svalbard. Well 7121/1-1, located slightly north of the Hammerfest Basin, penetrated thick intervals of middle/lower Triassic source rocks (Augustson 1993; Henriksen *et al.* 2011*b*). Based on seismic and well data, the Triassic source rock could be present over a wide area (Fig. 9). In the Upper Triassic section, seismic reflectors are generally more discontinuous, with rapid changes in amplitude indicating a terrestrial depositional environment. In some places, high-amplitude anomalies represent channel systems possibly of reservoir-quality sandstone and in some localities gas-bearing sandstone (Rønnevik and Jacobsen 1984; Gabrielsen *et al.* 1990; Henriksen *et al.* 2011*b*; Spencer *et al.* 2011).

Lower–Middle Jurassic sediments are represented by the Realgrunnen Subgroup (Fig. 2). They predate the major Kimmeridgian extensional tectonics and were deposited in marginal-marine to terrestrial environments (Olaussen *et al.* 1984). The sequence varies in thickness from 150–350 m in the eastern and central parts of the basin to more than 500 m along its the western border. More than 90% of the discovered hydrocarbons in the basin have been found in the Realgrunnen and Sassendalen groups, with reservoirs hosted by the Kobbe, Snadd, Fruholmen, Tubåen, Nordmela and Stø formations (Fig. 2).

Only a few wells have targeted the Cretaceous play, and only minor hydrocarbons have been encountered in this interval. The Cretaceous section is subdivided into two main units: pre-Albian and post-Albian (Figs 9 and 10). The lowermost pre-Albian interval is represented by an alternation of massive sandbodies and shale, deposited as delta fans and more passive infill in the basin (Figs 8 and 11). The depositional environment varies from shallow-marine to open-marine conditions (Grundvåg *et al.* 2017; Marin *et al.* 2017). In places, massive erosion of the surrounding Loppa High and Finnmark Platform took place after major Kimmeridgian rifting, resulting in mass-sediment transport into the Hammerfest Basin, potentially by sandy turbidity currents. However, shallow-marine transgressive shoreface deposits are suggested by Marín *et al.* (2018) in parts of the basin, and are proven by the well 7122/2-1. The post-Albian silty shale sediments were generally deposited in deeper-water environment. Potential sandstone units in the underlying Hekkingen Formation and the overlying Kolje Formation may be present locally. Although highly variable, the sand-rich part of the Knurr Formation (Ryazanian–Barremian) in places exceeds 100 m of high-quality reservoir sand located in depressions along the flanks of the Hammerfest Basin (Figs 8 and 11). There may still be a hydrocarbon potential in stratigraphic traps at the Lower Cretaceous level (Fig. 11).

The Tertiary section consists mostly of bathyal mudstones deposited during the Paleocene and Eocene. A gentle southward dip of the Tertiary clinoforms may indicate a larger uplift towards the north (Fig. 9). Deep erosion of the Loppa High probably resulted in the transport of silty and shaly sediments towards the south. Well 7121/1-1 also encountered minor sand in the Tertiary section.

The uppermost Quaternary section, derived mainly from glacial activity, varies in thickness from a few metres to around 200 m on the platform (Fig. 9). Along the continental margin, the sequence reaches thickness of 1000 m. A major Upper Regional Unconformity (URU) that cuts through the underlying intervals due to major glacial erosion represents the base of the Quaternary sediments. Evidence for several phases of glacial advances and retreats over the last million years is interpreted from the shallow section and from detailed bathymetric maps west of the Hammerfest Basin (Andreassen *et al.* 2008; Laberg *et al.* 2010, 2012; Rydningen *et al.* 2013).

Magmatism

No magmatism is observed in the basin. Traces of volcanic ash were documented in the Paleogene sediments of the Hammerfest Basin area; they may be related to volcanic activity farther west in connection with the opening of the Atlantic Ocean.

Heat flow

The geothermal gradient has been computed (in-house North Energy ASA) from 32 exploration wells in the Hammerfest Basin using bottom hole temperatures. The temperature gradient varies from around 30 up to 40°C km^{-1}, with an average gradient of 35°C km^{-1}. The geothermal gradient was used in producing the maturity map in Figure 12. Another study by Cavanagh *et al.* (2006*a*, *b*) indicated heat-flow values of 60 and 65 mW m^{-2} at maximum burial in order to match the vitrinite reflectance data from wells.

Petroleum geology

The Hammerfest Basin CTSE has proved to be a prolific petroleum province (Fig. 12). Two fields are in the production stage: the Snøhvit gas and gas-condensate fields, and the Goliat oilfield. Most of the 34 drilled exploration wells found hydrocarbon shows, and the discovery rate for the basin is 53%.

Discovered and potential petroleum resources

Almost 340 Msm^3 (2140 Mbbl) recoverable oil equivalent has so far been discovered in the basin, divided between 14 main structures (Fig. 13). In total, 18 discoveries were made, 11 of which contain liquids. In addition, 14 wells have hydrocarbon shows (http://www.npd.no). Most hydrocarbons were found in the Middle Jurassic sandstone interval, containing gas or gas with an oil leg. A significant part of the discovered oil in the Goliat Field is in the Kobbe reservoir of Anisian age, in addition to discoveries in the Upper Triassic–Jurassic section. Traces of gas were found in the deeper Permian section. Along the flank of the basin in the transition zone towards the Loppa High, minor oil and gas resources were encountered in the lower Cretaceous sequence (i.e. Myrsildre and Skalle discoveries).

After 35 years of exploration, a natural question to ask would be: are there are still more hydrocarbons to be found? No major discoveries have been made since the Goliat. Middle Jurassic play in the Hammerfest Basin is mature with respect to its exploration status. However, at other stratigraphic intervals, such as the Upper Permian, Middle–Lower Triassic and Lower Cretaceous, large areas are still undrilled and have not been studied in the same detail as the Middle Jurassic section. In the Goliat Field, oil was discovered in Middle Triassic sandstones. In order to understand the reservoir potential of Permian and Triassic plays, more detailed studies of their provenance need to be carried out. Sediments from the Fennoscandian Shield have proved to be of good reservoir quality (Mørk 1999; Henriksen *et al.* 2011*b*). Since the Hammerfest Basin has an asymmetrical shape, with the deepest parts located towards the north (Figs 5, 11 and 14), further exploration of the Triassic–Permian section may be productive in the southern and eastern parts of the basin. The reservoir quality may also be better in these areas due to lesser burial depth.

There are several small, undrilled structures in the Middle Jurassic play, with a limited volume potential. Some of the larger structures may still have hydrocarbon potential in the deeper Triassic reservoir interval in areas not penetrated by wells (Fig. 14). Along the flanks of the basin, structures consisting of Upper Permian sandstones may have a limited hydrocarbon potential. Burial depth and reservoir quality may be critical factors. Lower Cretaceous stratigraphic traps may have a moderate potential. Thick sandbodies deposited as submarine fans along the flanks of the basin (Figs 8 and 11) may have significant potential if stratigraphic traps are proven to be valid targets.

Within the different play types, a total remaining recoverable hydrocarbon resource of 100–200 Msm^3 may be possible in the basin (Fig. 15).

Current exploration status

The Hammerfest Basin TSE is still an interesting target for oil companies, although part of the basin is considered mature with regard to exploration. New licence acreages are being granted by the Norwegian Ministry of Petroleum and Energy through yearly Application of Predefined Areas (APA)

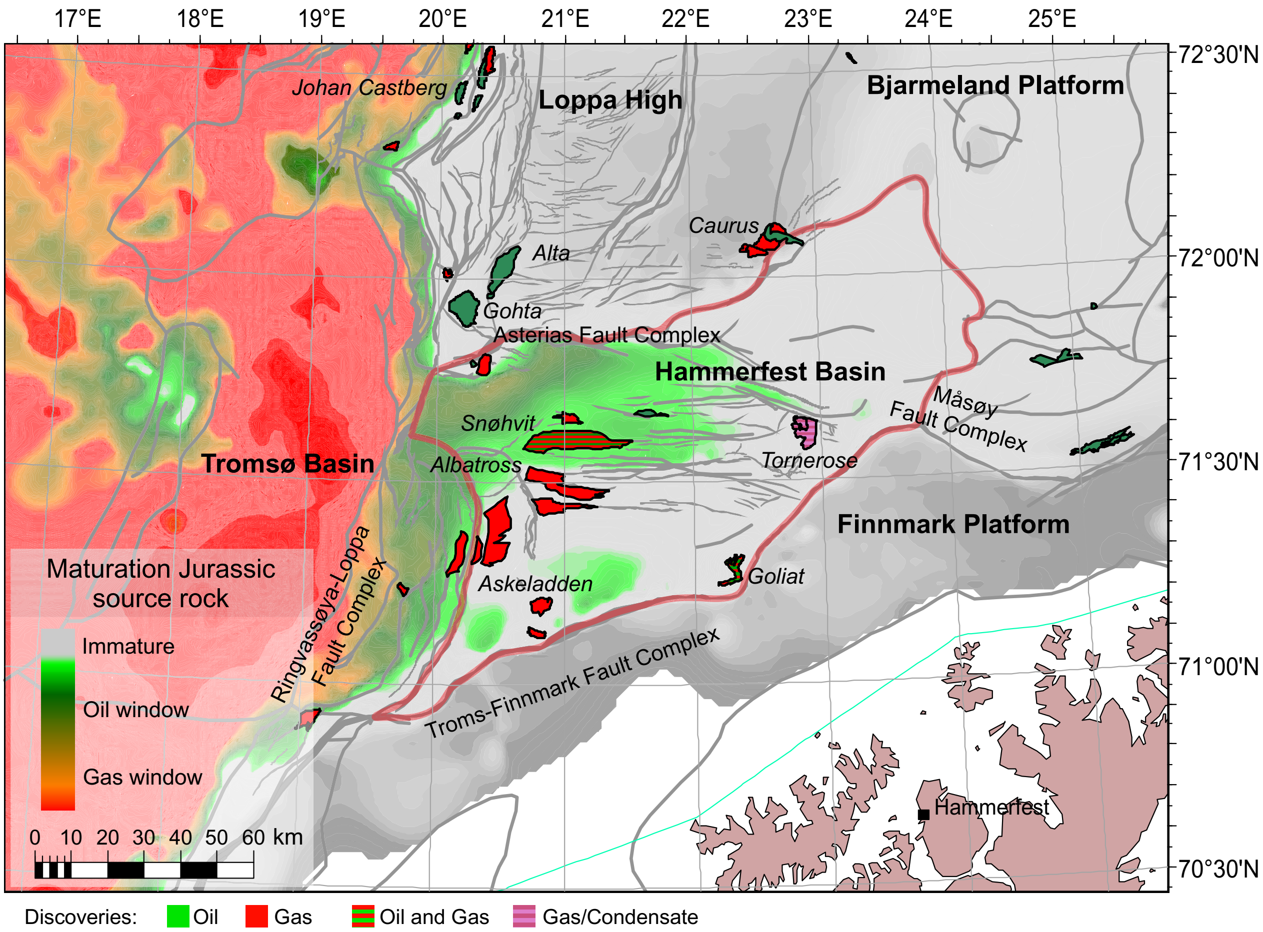

Fig. 12. Upper Jurassic Hekkingen source-rock maturation map based on present-day depth map, uplift maps from velocities and vitrinite reflectance data (Ktenas *et al.* 2017), and temperature and geochemical data from wells.

rounds. A large seismic and well database exists for the area (http://www.npd.no), allowing detailed studies to be carried out. The production infrastructure established in the area still makes the small- to moderate-sized structures attractive to industry. More exploration wells are expected

Hydrocarbon systems and plays

Several petroleum systems and plays are present in the Hammerfest Basin CTSE. Discovered hydrocarbons at different levels and different geochemical signature indicate multiple

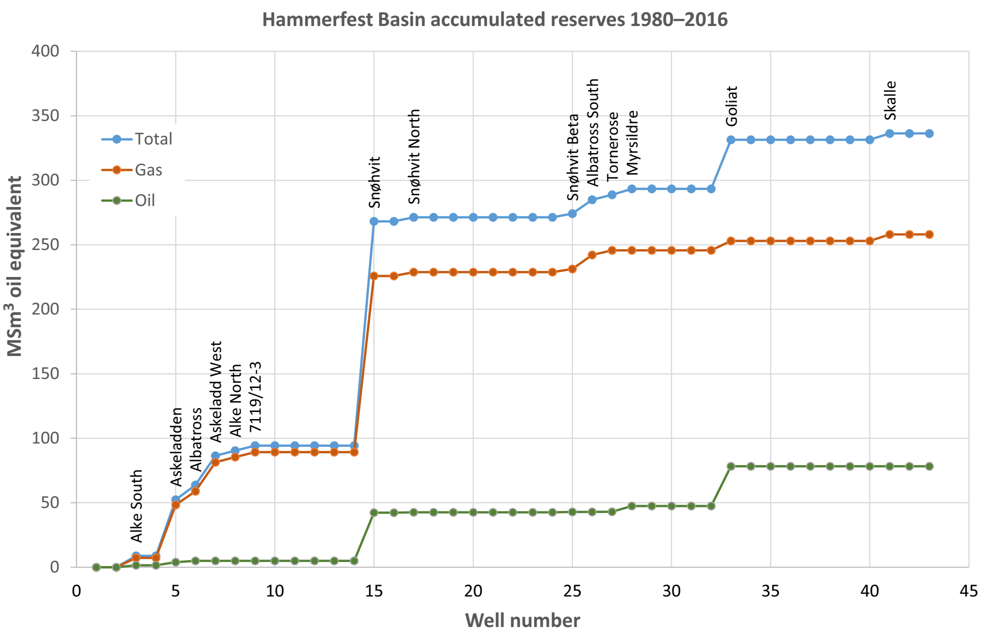

Fig. 13. Accumulated resources in the Hammerfest Basin from 1980 to 2016. Volumes are based on NPD published data (from http://www.npd.no).

(**a**)

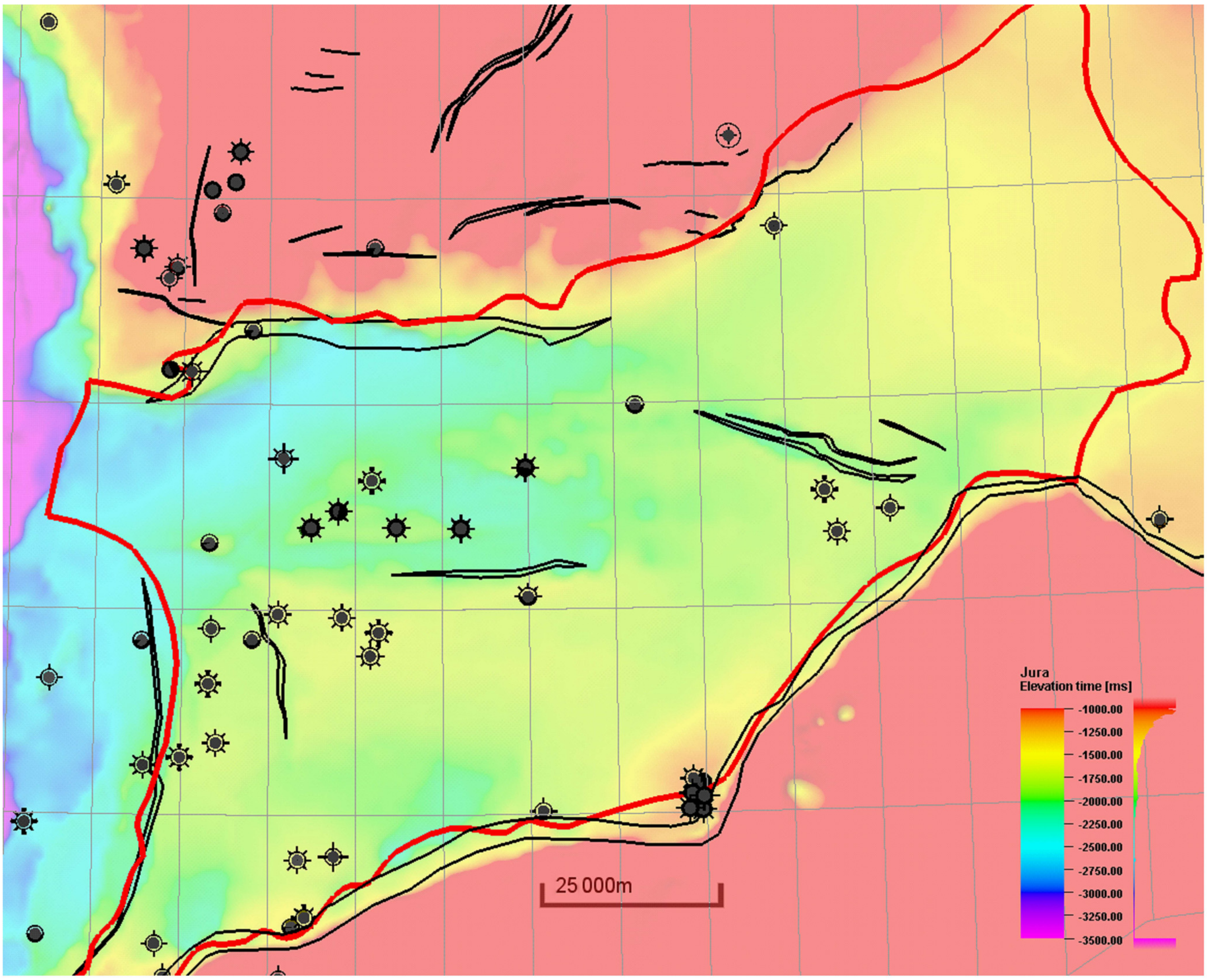

Fig. 14. Maps of different levels penetrated by wells. (**a**) Base Cretaceous Unconformity time map (Hekkingen Formation) with wells drilled into the Upper Triassic–Lower Jurassic pre-rift reservoir units.

systems. Snøhvit gas-condensate fields (comprising the Askeladden, Albatross and Snøhvit discoveries) and the Goliat oilfield seem to be sourced from both Triassic and Jurassic source rocks (e.g. Ohm *et al.* 2008; Duran *et al.* 2013). The Upper Jurassic source rock has been penetrated by all exploration wells and mapped on 3D seismic data over the entire basin. In addition, a significant part of the discovered oil in the Goliat Field has originated from Triassic source rocks, likely to be from the Middle Triassic Anisian interval. Wells further to the north (e.g. 7324/10 and 7121/1-1) have discovered Middle–Lower Triassic anoxic shales (Ohm *et al.* 2008; Henriksen *et al.* 2011*b*), confirming the source-rock potential of this interval. The areal extent and quality of this source rock is, however, still uncertain.

In general, normal pressure conditions exist in the area at present (Skagen 1993), with no major drilling challenges so far. Concerns about leakage and remigration of oils due to underfilled and emptied structures has been discussed for decades (e.g. Spencer *et al.* 1984, 2011; Nyland *et al.* 1992; Skagen 1993; Doré and Jensen 1996; Riis 1996; Brekke *et al.* 2001; Henriksen *et al.* 2011*a*, *b*; Hermanrud *et al.* 2014).

Source rocks. The Hekkingen Formation (Volgian–Ryazanian) represents the main source rock in the Hammerfest Basin. Long-distance hydrocarbon migration from the formation has provided the most important contribution for the petroleum charge in the area (Fig. 12). The widespread organic-rich Upper Jurassic Hekkingen Formation is the main source rock for the discovered hydrocarbons, and contains typical type II/III kerogen with total organic carbon (TOC) values of up to 20%. The thickness of the Hekkingen Formation varies from tens of metres to more than 200 m. The main kitchen area is located in the Tromsø Basin (Ryseth *et al.* 2021) and in the deepest part of the Hammerfest Basin to the NW. Based on reconstructions of the basin to maximum burial depth (Nyland *et al.* 1992; Henriksen *et al.* 2011*a*; Ktenas *et al.* 2017), it seems that the Upper Jurassic source rock has an oil potential only to the north and west of the basin (Fig. 12).

The Middle–Lower Triassic (Kobbe and Klappmyss formations) and Upper Permian intervals may also be important source rocks (Bjorøy *et al.* 2010). A significant part of the oil discovered in the Goliat Field has its origin in the Middle Triassic (Anisian–Olenekian) source rock. Although the geographical extent of this source rock is uncertain, it is generally located around 1000 m deeper than the Upper Jurassic source rock, which means that it will be in a mature stage for oil and gas generation in the entire basin. The Kobbe Formation source rock is characterized as a type II–type II/III kerogen with TOC values of 2–8% (Henriksen *et al.* 2011*b*). The thickness of the Kobbe Formation source rock has so far been

(**b**)

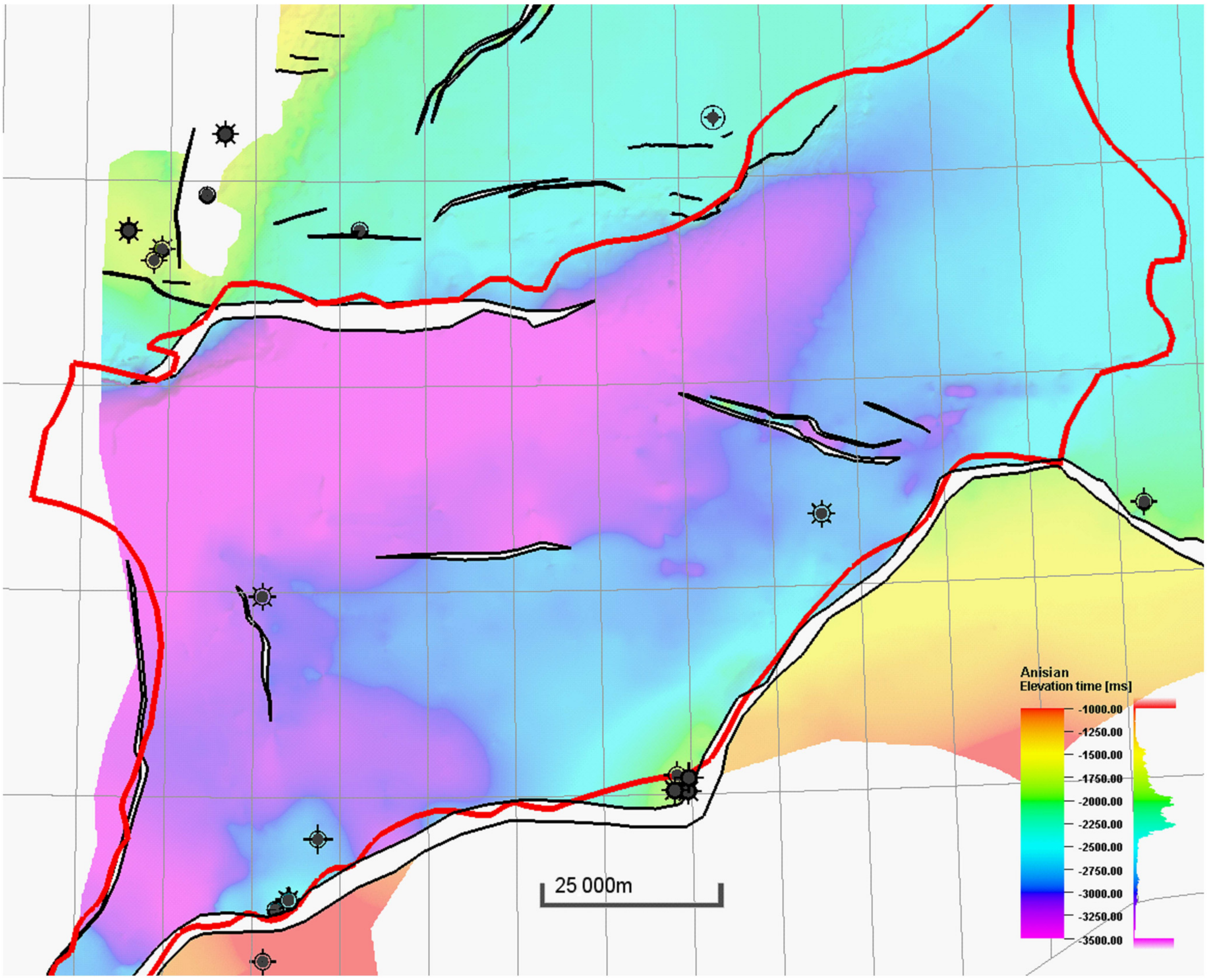

Fig. 14. *Continued*. (**b**) Top Anisian time map (Kobbe Formation) with wells penetrating the Lower Triassic.

identified to be in the range of 5–20 m. If present below structural and stratigraphic prospects with short vertical migration paths, it represents an attractive candidate for providing hydrocarbon charge. Wells on the Loppa High and the Bjarmeland Platform penetrated Upper Permian shale with source-rock potential. Although there is a high siliciclastic input in the Upper Permian succession, the Paleozoic source rock may still exist in parts of the Hammerfest Basin. Fossil oil columns have been observed in many of the drilled wells, and are an effect of uplift and erosion. In some wells, the fossil oil column exists below the structural closure, indicating tilting of the area. Several authors have discussed seal breaching in structures and the consequent leakage/remigration of hydrocarbons (Nyland *et al.* 1992; Riis and Fjeldskaar 1992; Brekke *et al.* 2001; Ohm *et al.* 2008; Duran *et al.* 2013; Hermanrud *et al.* 2014; Lerch *et al.* 2016).

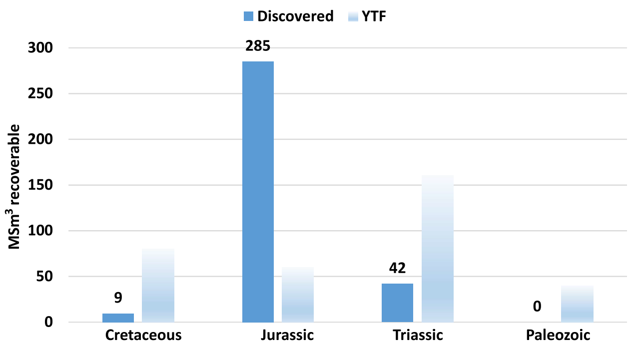

Fig. 15. Discovered recoverable resources in oil equivalents (source Norwegian Petroleum Directorate 2017) and estimated yet-to-find resources (this study) sorted by plays.

Reservoirs. The main proven reservoirs in the Hammerfest Basin are sandstones of Late Triassic–Middle Jurassic age (Figs 2 and 8). So far, most of the main discoveries have been made in the Realgrunnen Group, mainly in the Stø, Nordmela, Tubåen and Fruholmen formations. Due to the post-glacial uplift, the original maximum burial depth of these formations was 1000–1500 m deeper compared with their current depths. Consequently, the reservoirs have 5–10% lower porosity than expected for their present depths. This is important to account for and can be critical in estimating the reservoir properties in some intervals. The Jurassic reservoirs show a porosity range of 18–25% at depths of around 2000–2500 m, and a general permeability range varying from 50 mD to several hundred millidarcies. The thickness of the Jurassic reservoirs varies throughout the basin, from very thin or absent in the east and along the flanks of the basin to around 250 m to the west and along the border with the Tromsø Basin. Along the flank of the Hammerfest Basin (e.g. the Goliat area), most of the Jurassic Stø and Normela formations are completely eroded.

Additional reservoirs exist in Lower Cretaceous Ryazanian–Valanginian strata (Figs 2 and 8). These are thickly developed fan systems and exist mainly along the flanks of the basin. These fans were sourced from the Loppa High and the Finnmark Platform (Seldal 2005). Well 7120/1-2 revealed oil-bearing Volgian sand wedges. Detailed mapping of the Cretaceous–Upper Jurassic channels is vital in order to predict where sands were deposited in the basin.

Well 7120/12-2 shows a high frequency of alternating lithologies, which is representative of Triassic strata in the SW Barents Sea (Fig. 8). The main challenge is to predict thick enough reservoir sands that have not been too deeply buried. More deep wells combined with detailed mapping of depositional facies are needed in order to evaluate the exploration potential of Lower and Middle Triassic reservoirs.

In general, the Paleozoic section is deeply buried in the basin. The Permian carbonate units does not seem to have any reservoir potential, while the uppermost Permian consists of more than 100 m of siliciclastic sandstones of potential reservoir quality, even at depths greater than 3000 m (Fig. 8). A moderate exploration potential may exist but only in the shallow flanks of the basin.

Seals. Wells in the Hammerfest Basin have documented rocks with an excellent sealing potential in several stratigraphic intervals (Figs 2 and 8). In the Paleozoic section, Visean–Serpukhovian shales may be an important seal for the deepest sedimentary section. Shales at the Paleozoic–Mesozoic transition (Ørret–Havert formations) may be the most regional seal for the deep section. Within the thick Triassic section, several intervals may act as seals. The Kobbe Formation seal of Anisian age has proved to work in the Goliat Field. The Upper Jurassic and Lower Cretaceous shale represents a perfect top seal for the Jurassic horsts and rotated fault blocks, and has been proven to seal the numerous gas discoveries made in the basin. Paleocene and Eocene shales may have sealing potential across the basin but are most relevant along its flanks where they are juxtaposed with older reservoir units.

Traps. The main exploration successes in the Hammerfest Basin have come from drilling east–west-trending horst structures or rotated fault blocks related in the north–south-trending Ringvassøy-Loppa Fault Complex (Figs 5 and 7). All the Snøhvit Field segments are related to structural highs. The Goliat structure is related to a major listric fault, which started to develop simultaneously with the present-day configuration of the Hammerfest Basin as a part of the Troms Finnmark Fault Complex (Fig. 9).

Most wells in the basin have only penetrated stratigraphy down to Upper Triassic age (Fig. 14) with the Jurassic play as the main target. Additional hydrocarbon potential, especially gas, may still exist in the deeper fault-related traps or dome-shaped structures of Triassic and Permian age. The stratigraphic trap potential of the Middle Triassic and Lower Cretaceous–Upper Jurassic is underexplored in the basin but this may represent an interesting concept for the future.

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