Northern Svalbard Composite Tectono-Sedimentary Element

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Abstract: The Northern Svalbard Composite Tectono-Sedimentary Element (CTSE) comprises Proterozoic, Early Paleozoic and Devonian sedimentary rocks preserved in northern Svalbard and on the adjacent shelf margin between complexes of metamorphic and crystalline basement rocks. The Northern Svalbard CTSE covers four main tectono-sedimentary elements: Tonian synrift, Neoproterozoic–Cambrian post-rift, Ordovician passive margin and late Silurian?/Devonian synextensional basins. The oldest documented sedimentary strata are greywacke and shale deposited after the Greenvillian Orogeny and assumed to be younger than 980–960 Ma. The present CTSE further includes Cambrian–Ordovician sedimentary rocks in Ny-Friesland and Nordaustlandet, while the dominant part of the CTSE are continental Old Red Sandstone sediments of the late Silurian?/Early Devonian Red Bay and Siktefjellet groups and the Early–Late Devonian Andreé Land Group onshore northern Spitsbergen. Locally, the Cambrian–Ordovician formations contain petroleum source rocks with moderate total organic carbon contents and relatively high hydrogen index values, suggesting a good potential for oil generation. There are possible reservoirs, seals and traps in some of the basins but the CTSE generally holds a very limited potential as a petroleum province, particularly as the region is under strict environmental protection.

This contribution provides a summary of the current knowledge of the geology and hydrocarbon prospectivity of a Composite Tectono-Sedimentary Element (CTSE) constituting northern Svalbard and the shallow shelf area immediately north of the archipelago (Fig. 1). This CTSE principally comprises an area with local Proterozoic–Devonian basins and strata deposited prior to the latest Devonian (–earliest Carboniferous?) Svalbardian Tectonic Event of the Ellesmerian Orogeny (Harland and Wright 1979), preserved within areas of exposed metamorphic and crystalline basement rocks of Archean–Mesoproterozoic age (Hellman *et al.* 2001; Dallmann 2015) (Figs 2, 3). In the interior of the Northern Svalbard CTSE, there are also local occurrences of Miocene lava flows, as well as Quaternary volcanic centres and volcanoclastic deposits (Prestvik 1978; Skjelkåle *et al.* 1989; Tuchschmid and Spillmann 1992; Treiman 2012).

Tectonostratigraphic reconstructions in the Arctic for the Proterozoic and early Paleozoic times suffer from limited palaeomagnetic data, and several significant differences exist between the proposed palaeogeographical positions of the various basement terranes of the region (Smelror and Petrov 2018). Thick, conformable sedimentary successions and evidence of orogeneses and various deformational events are found in many places but ages of these deposits and events are often imprecise, and tectonostratigraphic correlations are debatable. This is also the case for the Northern Svalbard CTSE, where contradicting ideas and models have been presented on many occasions (Dallmann 2015; Braathen *et al.* 2018; Dallmann and Piepjohn 2020; Koehl *et al.* 2022; Koglin *et al.* 2022).

Age

The age of the sedimentary succession in the Northern Svalbard CTSE is Proterozoic–Devonian, comprising sediments deposited after the Grenvillian Orogeny and prior to the latest Devonian (–earliest Carboniferous?) Svalbardian Tectonic Event (Dallmann 2015).

Geographical location and dimensions

The Northern Svalbard CTSE covers the northern part of Spitsbergen, Nordaustlandet and the adjacent shallow shelf. The CTSE extends from the northern part of Dicksonfjorden and Ekmanfjorden in the south up to the northernmost parts of Spitsbergen and further east to northern Nordaustlandet (Fig. 1; Enclosure A).

Principal datasets

Wells

There has been no hydrocarbon exploration drilling on northern Svalbard but some investigations for metals (copper and gold) and industrial minerals (baryte and muscovite) have been carried out during the last century (Saalmann 2016).

Seismic data

Seismic data are limited but two seismic sections from on a survey by Statoil in the 1980s document the presence of Devonian strata in offshore basins north of Spitsbergen (ST8515R87STK-101) and in Bockfjorden–Woodfjorden (ST8515R87STK-103/105) (Dallmann and Piepjohn 2020, fig. 84). Along a seismic refraction profile (i.e. profile AWI-99300) at the northwestern offshore border of the present CTSE and towards the Yermak Plateau, Ritzmann and Jokat (2003) inferred the presence of Late? Silurian/Devonian sedimentary basins beneath the Cenozoic sediments (Fig. 4).

Outcrop and subsurface studies

The principal datasets from northern Svalbard include geological maps to the scale of 1:100 000 (Spitsbergen part) and 1:200 000 (Nordaustlandet part) (see the overview in

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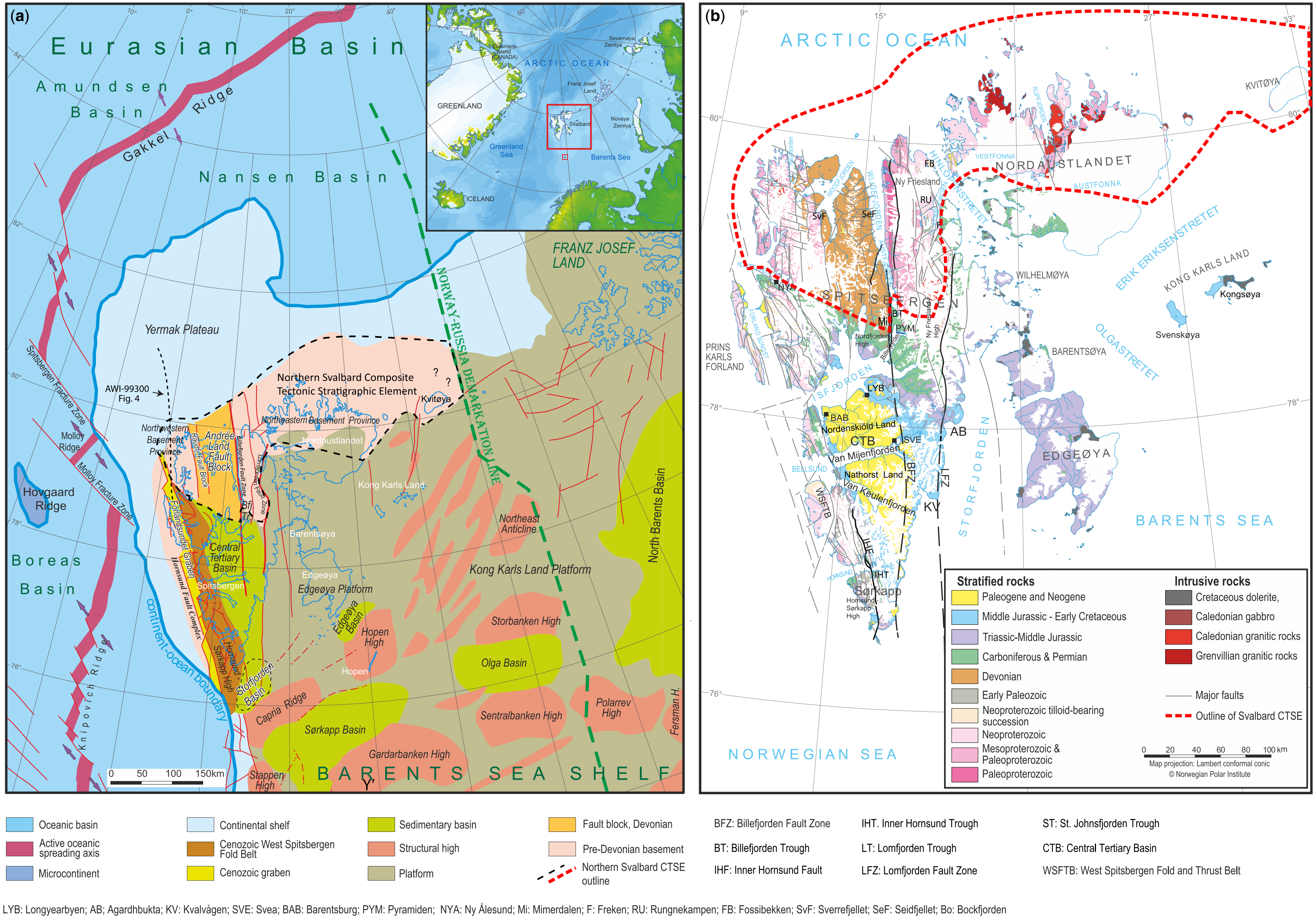

Fig. 1. Geographical position and outline of the Northern Svalbard Composite Tectono-Stratigraphic Element (CTSE).

Dallmann 2015), field reports, and scientific publications (see the list of papers in bibliography 6-2–6-4 in Dallmann 2015; Enclosures B–D).

The present aeromagnetic maps shown in Figure 3 are compilations of available aeromagnetic data acquired with various resolutions over the last four decades (Olesen *et al.* 2010; Gaina *et al.* 2011; Gernigon *et al.* 2014; Dumais *et al.* 2020, 2022; Dumais and Ofstad 2022).

The gravity map shown in Figure 3c is a compilation of available data where the global gravity model Sandwell v23-1 was used for latitudes south of 80° N (Sandwell *et al.* 2014). North of 80° N, the Arctic Gravity Project (ArcGP) data compilation with a 5 arc-min resolution (Kenyon *et al.* 2008) has been merged with the Oasis Montaj Gridknit algorithm (Geosoft 2013).

The available datasets also include international and regional compilations of geological and geophysical data of the Circum-Arctic (Harrison *et al.* 2008; Gaina *et al.* 2011, 2014; Petrov *et al.* 2016, 2018, 2021).

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

North of Svalbard, a major fault and its eastward extension separates the Northern Svalbard CTSE from the Eurasian Arctic Rifted Margin CTSE to the north (Abdelmalak *et al.* 2024) (Fig. 1). In the northernmost area of Spitsbergen, a possible offshore extension of the Devonian Andrée Land Basin appears on a seismic line from a Statoil survey carried out in the 1980s (ST8515R87STK-101) (Dallmann and Piepjohn 2020). On the northern margin, both potential field and seismic data support the indication that basins of the Late Silurian?/Devonian ORS succession continue northwards onto the shelf (Figs 3 & 4). Moreover, Devonian sedimentary and metamorphic rocks have been found in dredge samples on the Yermak Plateau (Riefstahl *et al.* 2013; Kristoffersen *et al.* 2020) and in the deepest part of the Nansen Basin (Smelror *et al.* 2022). However, the Yermak Plateau is not included in the present Northern Svalbard CTSE. The presence of lower Paleozoic sediments on the shelf between the Svalbard and Franz Josef Land archipelagos is not documented, and the eastern boundary of the present CTSE is thus uncertain. On Franz Josef Land, Carboniferous carbonates unconformably cap greenschist-facies siliciclastic metasediments of possible Ediacaran–early Cambrian age (Dibner 1998; Knudsen *et al.* 2019).

To the west, the boundary aligns with the eastern boundary of the West Barents Sheared Margin CTSE (Faleide *et al.* 2024) (Figs 1 & 3). The boundary follows the western limit of the Northwestern Basement Province (Dallmann 2015) and the northern offshore extension of the Hornsund Fault Zone (Kristoffersen *et al.* 2020). In the SW, the southern boundary of the present CTSE aligns with the northern boundary of the Svalbard CTSE (Olaussen *et al.* 2023). Its southeastern boundary aligns with the northwestern boundary of the North Barents CTSE (Lundschien *et al.* 2023) and the northwestern corner of the East Barents CTSE. The combined eastern boundary of the present CTSE and the North Barents CTSE coincides with the Caledonian suture. The southern boundary of the Northern Svalbard CTSE principally follows the boundary between outcropping sedimentary rocks to the south and metamorphic and crystalline basement rocks to the north (Sigmond and Roberts 2007). The Carboniferous–Triassic sedimentary units occurring on either side of the Hinlopenstretet (i.e. strata within and east of the Lomfjorden Fault Zone on northeastern Spitsbergen and on the southern part of Nordaustlandet) are not included in the present CTSE but are assigned to the Svalbard CTSE (see Olaussen *et al.* 2023).

The main tectonic events and erosional and depositional phases in the Northern Svalbard CTSE are summarized in Figure 2 (see also Enclosures E–F). Following the late orogenic volcanism and uplift after the Grenvilian Orogeny in the Stenian–Early Tonian, rifting and post-rift thermal subsidence took place along the northern Laurentian margin in the Tonian. The CTSE further covers strata deposited during the global Proterozoic extensive glaciations in the Cryogenian (i.e. the Sturtian glaciation *c.* 717–661 Ma) and Ediacaran (i.e. the Marinoan glaciation, *c.* 651–635 Ma), and in the Cambrian at the opening of the Iapetus Ocean. During the Early Ordovician, parts of the CTSE formed a stable carbonate platform along the Iapetus margin of Laurentia, prior to the Caledonian Orogeny in the Silurian and the Svalbardian event of the Ellesmerian Orogeny in the latest Devonian–earliest Carboniferous (Fig. 2). The Northern Svalbard CSTSE can be subdivided into four separate second-order tectonic stratigraphic elements (TSE), separated by major tectonic lineaments and/or major stratigraphic breaks: (1) a Tonian synrift TSE and its related rift-basin sedimentary succession; (2) a Neoproterozoic–Cambrian post-rift TSE and an associated sag-basin infill succession; (3) an Ordovician passive-margin TSE and related sedimentary strata; and (4) a late Silurian?/Devonian post-orogenic TSE comprising several synextensional basins and their infill sequences (Fig. 2).

The Neoproterozoic succession is comparable to contemporaneous strata in Greenland and in Finnmark in Northern Norway and includes several levels of tillites attributed to global glaciations in the Cryogenian and Ediacaran (Gee and Teben'kov 2004; Gasser 2014; Grundvåg and Skorgenes 2022). The overlying Cambrian–Ordovician succession is part of large, supra-regional carbonate platform that developed at the northeastern margin of Laurentia following the glaciations (Fortey and Bruton 1973; Stouge *et al.* 2011). Onshore northern Spitsbergen, large parts of the CTSE are dominated by Late Silurian?/Devonian continental red beds, commonly referred to as the Old Red Sandstone (ORS) succession, which is preserved in a series of fault-bounded basins within the Proterozoic basement (Dallmann and Piepjohn 2020). Newly discovered large detachment zones in the westernmost sub-basin of the ORS succession in northern Svalbard may suggest a similar development as post-orogenic extensional collapse/supra-detachment basins described elsewhere in the Scandinavian–Greenland Caledonides (Braathen *et al.* 2018; Maher *et al.* 2022). To some extent, this model contradicts previous basin models, which emphasize Early Devonian strike-slip motion (i.e. sinistral transtension: Dallmann and Piepjohn 2018).

Underlying and overlying rock assemblages

Age of underlying consolidated basement or youngest underlying unmetamorphosed rock unit

The present CTSE includes the oldest known Neoproterozoic sedimentary rocks on northern Svalbard. Low- and high-grade metamorphic basement rocks of Archean–Mesoproterozoic age underlie the present CTSE strata.

Age of oldest overlying rock unit

The youngest sedimentary strata of the Northern Svalbard CTSE are Late Devonian-aged continental deposits of the ORS succession preserved in a fault-bounded basin on Andrée Land. Locally, Neogene–Quaternary volcanic rocks and glacigenic sediments overlie the Northern Svalbard CTSE. In addition, Cenozoic deposits occur in the offshore areas north and

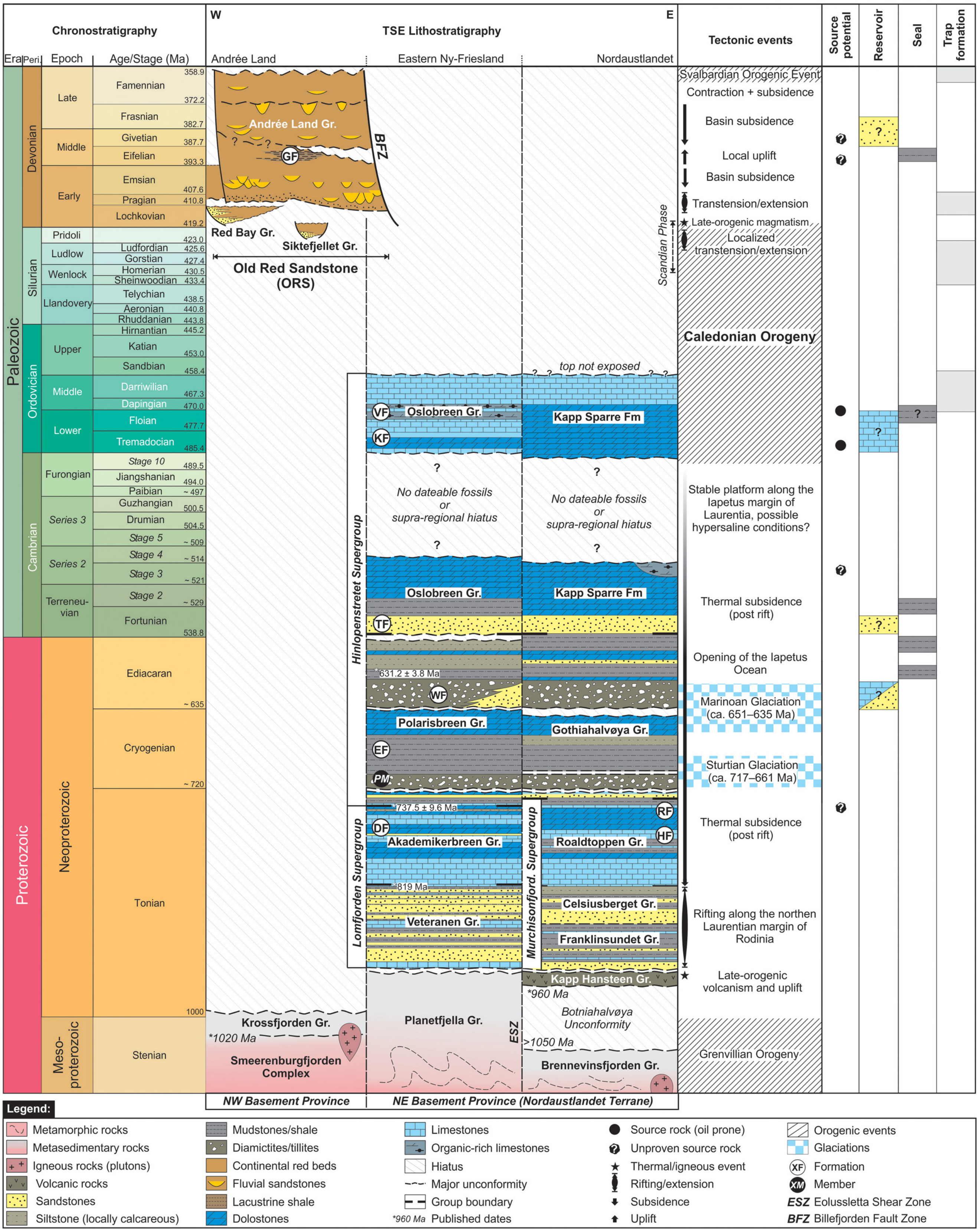

Fig. 2. Lithostratigraphy and petroleum geology of the Proterozoic–Early Paleozoic successions within the Northern Svalbard CTSE. Source: compiled from Harland *et al.* (1966, 1988), Hambrey (1982), Knoll (1982*a*, *b*), Knoll *et al.* (1991), Ohta (1994), Harland (1997), Halverson *et al.* (2004), Stouge *et al.* (2011), Berry and Marshall (2015), Dallmann (2015), Fairchild *et al.* (2016*a*, *b*, 2022), Krüger *et al.* (2017), Dallmann and Piepjohn (2020), Abay *et al.* (2022), and Millikin *et al.* (2022).

NE of Svalbard (e.g. Eiken 1993; Ritzmann and Jokat 2003; Geissler and Jokat 2004; Lasabuda *et al.* 2018).

Subdivision and internal structure

The onshore part of the Northern Svalbard CTSE is subdivided into four main provinces, namely the Northwestern and Northeastern basement provinces, which are separated by large-scale north–south-trending strike-slip faults that were active during the Caledonian Orogeny, and the Raudfjorden Trough and the Andrée Land Basin, both of which are Devonian-aged, fault-bounded basins occurring between the two basement provinces (Figs 1 & 2; Enclosure F).

The Northwestern Basement Province comprises metasedimentary rocks of Mesoproterozoic age: that is, the Krossfjord Group deposited between 1200 and 960 Ma (Stenian–Tonian) and intruded by *c.* 960 Myr old granitoids (i.e. during the Tonian). Traditionally, the province has been divided into the Albert I Land and the Biscayarhalvøya terranes but new detailed geochemical and structural work presented by Koglin *et al.* (2022) indicate the presence of a possible third terrane, named the Germaniahalvøya Terrane. The Northwestern Basement Province experienced up to high-grade metamorphism during the Caledonian Orogeny and is not dealt with in further detail herein.

Towards the east, the Raudfjorden Fault separates the Northwestern Basement Province from the Devonian Raudfjorden Trough. The Raudfjorden Trough is a NNW–SSE-trending, 90 km-long and up to 15 km-wide basin, with a Pridoli(?)–Lochkovian-aged sedimentary fill (i.e. the possible uppermost Silurian–Lower Devonian Siktefjellet and Red Bay groups), located between the Raudfjorden and Breibogen faults.

The Andrée Land Basin is a NNW–SSE-orientated, 170 km-long and up to 60 km-wide Devonian basin containing a several kilometres of a thick Early–Late Devonian sedimentary succession (Dallmann and Piepjohn 2020). The basin is exposed in the Andrée Land Fault Block, between the Raudfjorden Block in the west and the Billefjorden Fault Zone to the east, which separates it from the uplifted Proterozoic basement rocks of Ny-Friesland.

Traditionally, the Northeastern Basement Province has been subdivided into the Western Ny-Friesland and the Nordaustlandet terranes, which is separated by the Eolussletta Shear Zone (Dallmann 2015) (Fig. 3). The Western Ny-Friesland Terrane is composed of a series of thrust sheets consisting of Paleoproterozoic high-grade metamorphic rocks intruded by granitoids and Mesoproterozoic medium- to high-grade metamorphic and igneous rocks (i.e. the Planetfjella Group/Atomfjella Complex: Dallmann 2015), and it is not included in the CTSE. The Nordaustlandet Terrane, which includes the easternmost part of Ny-Friesland, northern Nordaustlandet and the adjacent smaller islands, host a *c.* 7.1 km-thick Neoproterozoic succession that is preserved on both sides of Hinlopenstretet, covering large parts of eastern Ny-Friesland and the western and central parts of Nordaustlandet. A more than 1 km-thick succession of Cambrian and Ordovician rocks is also present within the Nordaustlandet Terrane, exposed on either side of Hinlopenstretet (Dallmann 2015).

Sedimentary fill

Total thickness

The maximum total thickness of the sedimentary successions in northern Svalbard amounts to *c.* 12–14 km. This number is compiled from published data which often take into account the potential structural thinning or thickening connected with the Caledonian or Eurekan orogenies that affected the study area. Hence the thickness estimates in this CTSE are likely to be an insecure estimation for some of the lithostratigraphic units and of the total thickness.

Lithostratigraphy and depositional systems

The following basin fill summary pertains only to sedimentary strata preserved in the Northeastern Basement Province, particularly the Neoproterozoic–Ordovician succession of the Nordaustlandet Terrane, as well as the Late Silurian?/Devonian basin-fill successions (Figs 2 & 5). The Mesoproterozoic metasedimentary rocks of the Northeastern and Northwestern basement provinces (i.e. the Planetfjella Group and the Krossfjord Group, respectively) are not included in the present CTSE.

The Nordaustlandet Terrane includes around 7 km of Neoproterozoic (1000–541 Ma) sedimentary rocks overlying a nearly 5 km-thick Mesoproterozoic (1600–1000 Ma) succession of medium- to high-grade supracrustal and volcanic rocks (Dallmann 2015). In eastern Ny-Friesland, the Neoproterozoic succession includes limestone, sandstone, shale and volcanics of the Veteranen Group (lower–middle Tonian), and limestone, dolostone, conglomerate and shale of the Akademikarbreen Group (middle–upper Tonian), collectively referred to as the Lomfjorden Supergroup, as well as dolostone, sandstone, shale and conglomerate of the Polarisbreen Group (Cryogenian–Ediacaran), which is overlain by Cambrian–Ordovician dolostone, sandstone, shale and limestone of the Oslobreen Group (e.g. Harland *et al.* 1966, 1993; Ohta 1994; Halverson *et al.* 2004; Dallmann 2015; Krüger *et al.* 2017; Fairchild *et al.* 2022) (Fig. 2). The latter two units are assigned to the Hinlopenstretet Supergroup (Fig. 2).

The Neoproterozoic–Ordovician succession on Nordaustlandet has been assigned separate lithostratigraphic names (at the group and formation rank: Fig. 2). This is because of the structural complexity of the area, especially across the Hinlopenstretet, which makes a correlation to the Neoproterozoic–Ordovician succession on Ny-Friesland dubious. However, the many similarities leave little doubt as to their lateral stratigraphic relationship.

The Neoproterozoic succession on Nordaustlandet is divided into the Tonian Murchisonfjorden Supergroup, which is equivalent to the Lomfjorden Supergroup on Ny-Friesland, and the Cryogenian–Ordovician Hinlopenstretet Supergroup (Fig. 2). The lower part of the Murchisonfjorden Supergroup consists of intercalated quartzitic sandstones, shales and calcareous limestones, as well as subordinate conglomerates. Occasional ripple-scale cross-bedding indicates a shallow-marine origin for some of the sandstones. The upper part of the unit, assigned to the Roaldtoppen Group, is dominated by limestones and dolostones. The Cryogenian–Ordovician Hinlopenstretet Supergroup consists of a mixture of siliciclastic and fossiliferous carbonate rocks, and includes Cryogenian tillites (e.g. Harland *et al.* 1993; Dallmann 2015) (Fig. 2).

On Ny-Friesland, detailed sedimentological, palaeontological and geochemical studies have been carried out on the Tonian Akademikarbreen Group, including the dolomitic conglomerates of the upper Tonian Draken Formation, where stromatolites, oolites and pisolites are common, and well-preserved microfossils are found in silicified shards of microbial mats. These beds were deposited in a lagoonal environment occasionally swept by storms (Knoll 1982*a*; Knoll *et al.* 1991). A carbon isotope shift, which is recognized globally, is recorded in the lower–middle part of the Tonian carbonate succession, possibly reflecting transient eustatic sea-level fluctuations coupled with changes in nutrient

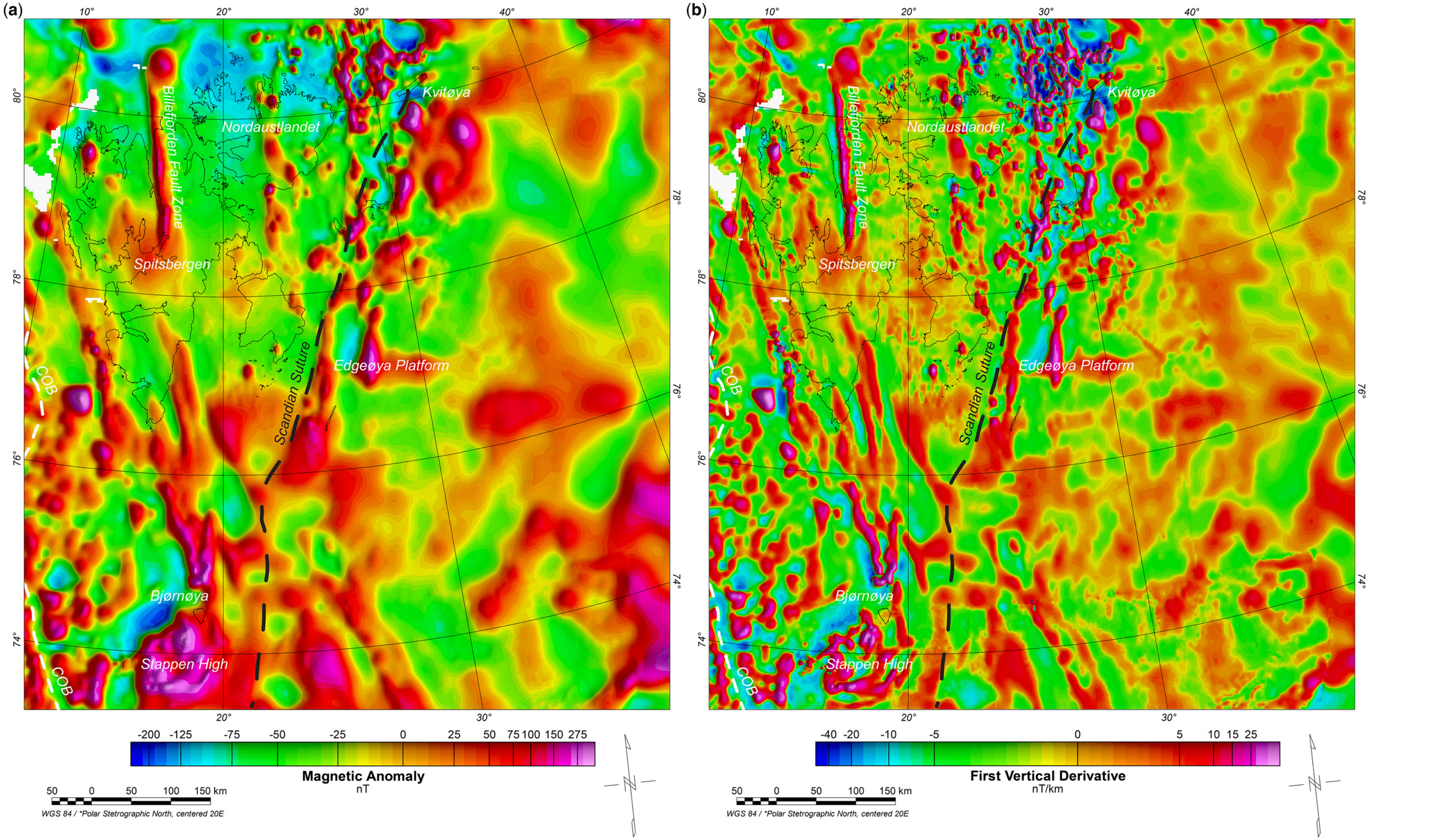

Fig. 3. Geophysical maps: (**a**) magnetic anomaly, (**b**) first vertical derivative of the magnetic anomaly, (**c**) free-air anomaly and (**d**) regional magnetic anomaly map. On maps (a)–(c) the continental–ocean boundary (COB) is shown with a white dashed line, as proposed by Dumais *et al.* (2020, 2022), on each side of the Knipovich Ridge and is based on the magnetic signature north and south of the Knipovich Ridge. The Scandian suture, shown with a black dashed line, is interpreted to be east of Svalbard and Nordaustlandet (Barrère *et al.* 2009, 2011; Gernigon *et al.* 2014). (**a**) The magnetic data show strong anomalies associated with known magmatic structures such as the sills located east of Nordaustlandet and possible dykes located in the Edgeøya Platform. Wide low magnetic anomalies are associated with the presence of sedimentary basins. (**b**) The first vertical derivative of the magnetic anomaly highlights the variation in the physical magnetic properties of the subsurface and is sensitive to the edges of the causal sources. Magnetic domains with shallow response (short wavelengths) can be separate from those with deeper response (longer wavelengths). Fault and oceanic fracture zones show clear elongated signatures on the first vertical derivative of the magnetic anomaly (e.g. BFZ).

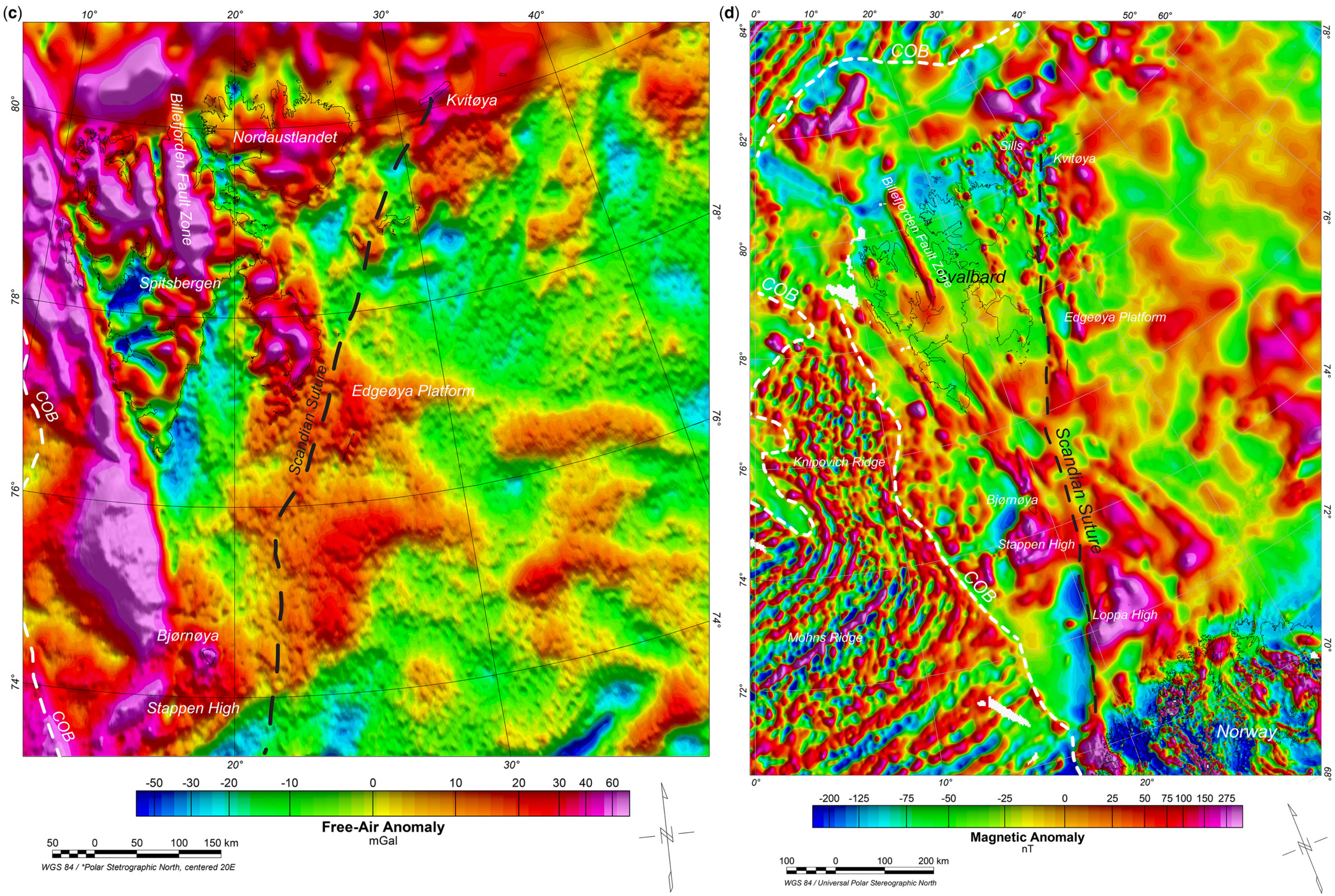

Fig. 3. *Continued*. (**c**) The free-air anomaly of the gravity data is sensitive to the density variation in the subsurface and the mass associated with the ice cap. In the subsea regions, the free-air gravity lows are associated with shallow–deep sedimentary basins. (**d**) On the map, the COB is shown with a white dashed line (see above), and the Scandian suture, shown with a black dashed line (see above), is interpreted from the Norwegian mainland to east of Nordaustlandet (Barrère *et al.* 2009, 2011; Gernigon *et al.* 2014).

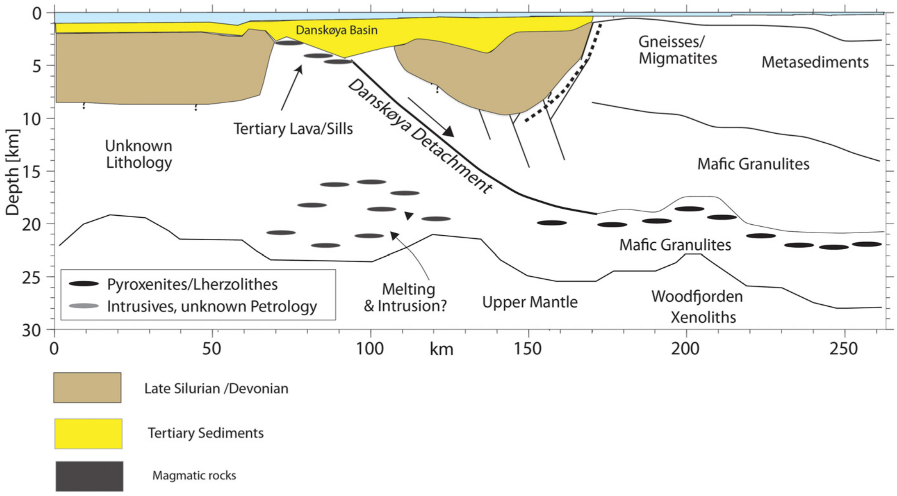

Fig. 4. Inferred Late Silurian–Devonian sedimentary basin offshore northwestern Svalbard and the adjacent Yermak Plateau as interpreted along profile AWI-99300 by Ritzmann and Jokat (2003). The thick black line marks the location of a proposed Cenozoic detachment fault. The dashed black line marks a possible north-dipping Caledonian Fault. Source: redrawn from Ritzmann and Jokat (2003).

delivery and ocean-circulation patterns caused by inertial interchange true polar wander events (Halverson *et al.* 2007). In the lateral- and age-equivalent Roaldtoppen Group (Tonian) on Nordaustlandet, the Hunnberget Formation exhibits a shallowing-upward carbonate sequence, where open-marine limestones pass upwards into columnar stromatolitic bioherms, which are overlain by lagoonal dolomites (Knoll 1984). These deposits are conformably followed by dolomite and bituminous limestones of the Ryssøy Formation deposited in coastal carbonate environments (Knoll and Calder 1983).

The Cryogenian–Ediacaran Polarisbreen Group comprises the upper 1 km of the Neoproterozoic strata in northeastern Spitsbergen (Fig. 2), and it contains an unusual complete record of Cryogenian glacimarine deposits recording the Marinoan glaciation and the subsequent cap-carbonate platform development (Halverson *et al.* 2004; Fairchild *et al.* 2022). Within the Cryogenian interval, non-marine carbonates, including microbial mats, deposited in fluvial to lacustrine and peritidal environments intercalate with glaciomarine deposits (i.e. the Petrovbreen Member of the Elbobreen Formation) and tillites (i.e. the upper Cryogenian Wilsonbreen Formation), suggesting that the strata accumulated in a glaciated basin that formed in the late stage of the global glaciation (Hambrey 1982; Halverson *et al.* 2004, 2018; Fairchild *et al.* 2016*a*, *b*, 2022; Fleming *et al.* 2016; Millikin *et al.* 2022). Combined, the Neoproterozoic successions on Nordaustlandet and Ny-Friesland have provided good records of both benthic and planktonic life found in different open coastal to intertidal environments, and have given important integrated information on changing physical and geochemical conditions and evolution of Proterozoic biotas, both prior to and within the so-called Snowball Earth glaciations (Halverson *et al.* 2004, 2007, 2018; Riedman *et al.* 2014; Tahata *et al.* 2015; Fairchild *et al.* 2016*a*, *b*, 2022; Millikin *et al.* 2022).

On eastern Ny-Friesland, the Cambrian–Ordovician succession of the Oslobreen Group reaches a thickness of *c.* 1.1 km and includes the early Cambrian Tokammane Formation, the Tremadoc–Floian Kirtonryggen Formation and the late Floian–Darriwilian Valhallfonna Formation (Harland *et al.* 1988; Stouge *et al.* 2011; Krüger *et al.* 2017) (Fig. 2). The succession consists of shallow-marine siliciclastic deposits in its lower part, passing upwards into shallow-marine warm-water carbonate platform deposits (Stouge *et al.* 2011; Krüger *et al.* 2017; Abay *et al.* 2022). Within the succession there is a marked lithological change between the white limestone beds of the Kirtonryggen Formation and the black even-bedded limestone and interbedded shale comprising the lower part of the overlying Valhallfonna Formation. This change in facies is probably due to a relative rapid increase in water depth (Fortey and Bruton 1973). The Kapp Sparre Formation in Nordaustlandet (*sensu* Stouge *et al.* 2011) appears to be equivalent to the Oslobreen Group on Ny-Friesland (Fig. 2).

The Devonian ORS succession of the present CTSE is preserved in the central part of northern Spitsbergen, bounded in the east by the north–south-trending Billefjorden Fault Zone and by the sub-parallel Raudfjorden Fault in the west (Harland *et al.* 1988; Braathen *et al.* 2018; Dallmann and Piepjohn 2020). Within this prominent ORS succession, well-preserved sedimentary structures and common fossils (plants, invertebrates and vertebrates) provide good means for detailed reconstructions of depositional environments and history (e.g. Moody-Stuart 1966; Friend *et al.* 1997; Blomeier *et al.* 2003; Piepjohn and Dallmann 2014; Berry and Marshall 2015; Dallmann 2015; Dallmann and Piepjohn 2020; Anfinson *et al.* 2022). The ORS succession comprises the Siktefjellet Group of possible late Silurian age, the overlying Lower Devonian Red Bay Group (Lochkovian) and the Lower–Upper Devonian Andrée Land Group (Pragian–Frasnian: Dallmann 2015; Dallmann and Piepjohn 2020) (Fig. 2). These are preserved in the two separate tectonic blocks separated by the north–south-trending Breibogen Fault: the Raudfjorden Block in the west, which hosts the Raudfjorden Trough, and the significantly larger Andrée Land Block in the east, which hosts the Andrée Land Basin.

For the Raudfjorden Block, Braathen *et al.* (2018) suggested that the Keisarhjelmen extensional detachment (being linked with the Raudfjorden Fault) truncates medium-grade metamorphic units overlain by possible late Silurian(?)–Early Devonian sediments, and places them in tectonic contact with the underlying high-grade gneiss complex. The Devonian strata, separated into several rotated fault blocks, apparently dip moderately southwards into the detachment for more than 30 km. However, this model is debated, and other workers prefer a model involving a strong component of transtensional strike-slip faulting (Dallmann and Piepjohn 2018, 2020). The sedimentary infill of the Raudfjorden Trough contains up to 6 km of late Silurian(?)–Early Devonian-aged conglomerates and sandstones assigned to the Siktefjellet Group and, dominantly, the overlying Red Bay Group (Friend *et al.* 1997; Dallmann 2015; Dallmann and Piepjohn 2020). The Siktefjellet Group consists of breccias and conglomerates of the Lilljeborgfjellet Formation, recording deposition near fault scarps, and fluvial sandstones of the Albertbreen Formation. The base of the Lilljeborgfjellet Formation is the main post-Caledonian angular unconformity, with depositional contacts on metamorphic rocks of both Biscayarhalvøya and the

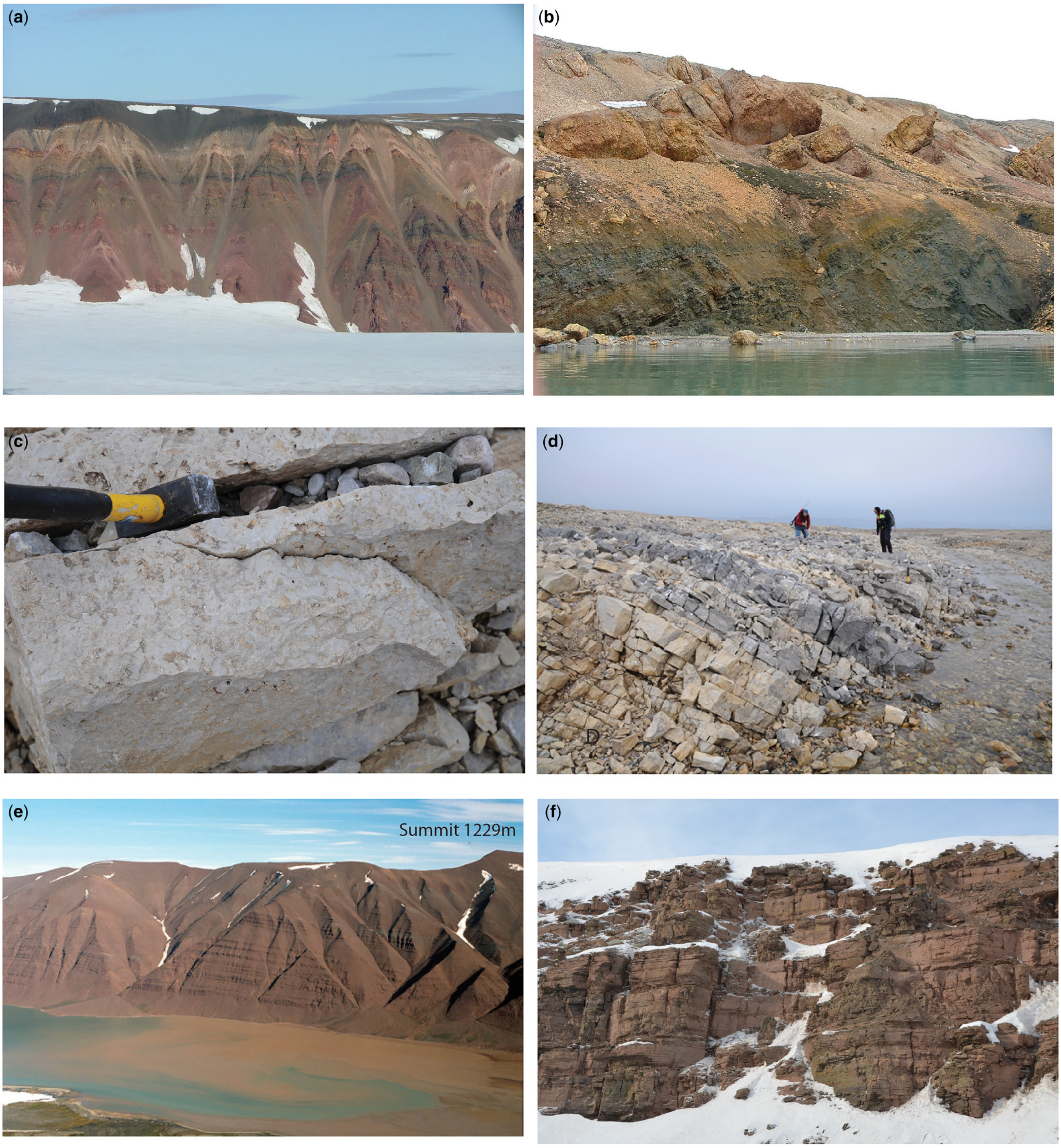

Fig. 5. Outcrops of Neoproterozoic, Cambrian, Ordovician and Devonian strata with potential reservoir bodies on Northern Svalbard. (**a**) Mixed sandstone and shale from the Torian Veteran Group. The multicoloured sandstone in the lower part represents the Kortbreen Formation and is capped by the dark shale of the Kingbreen Formation. Rungnekampen (RU in Fig. 1b). Northern part of Ny Friesland. (**b**) Neprotereozoic heterolithic carbonate shale facies overlain by massive carbonate beds with stromatolites, Akademiker Group. North face of the Freken Mountain (F in Fig. 1b). SE in the Lomfjorden. (**c**) Vuggy porosity and fractured dolomite in the Cambrian shallow-marine Tokammane Formation. Fossilbekken (FB in Fig. 1b). NE coast of Ny Friesland. (**d**) Fractured bedded limestone and dolomite of the Lower Ordovician Kirtonryggen Formation. Peritidal to shallow-marine facies on an inner part of a carbonate ramp. Fossilbekken (FB in Fig. 1b). NE coast of Ny Friesland. (**e**) Typical red beds in the northwestern part of Spitsbergen. Bedded alluvial deposits assigned to the Pragian–Emsian Wood Bay Formation. Bockfjorden (Bo in Fig. 1b). (**f**) A 10 m-thick cliff of Upper Devonian, probably Fammenian, alluvial-plain deposits with a high net fine–medium grained sandstone/shale ratio. Small stream channels are accompanied by finer-grained overbank deposits. Andre Land Group. Inner Mimerdalen (Mi in Fig. 1b). Source: (a), (b) photographs by Winfried Dallmann; (c), (d) photographs by Snorre Olaussen; (e) photograph by Winfried Dallmann, reproduced courtesy of the Norwegian Polar Institute; and (f) photograph by Erik P. Johannessen.

Albert I Land terranes (Dallmann and Piepjohn 2020). The Red Bay Group is mostly exposed along the eastern margin of the Raudfjorden Trough, and is dominated by thick conglomerate and sandstone successions of alluvial fan and braidplain origin (e.g. Friend *et al.* 1997; McCann 2000; Dallmann 2015; Dallmann and Piepjohn 2020). The group is subdivided into six formations: the Wulffberget, Rabotdalen, Prinsesse Alicef-jellet, Andréebreen, Frænkelryggen,and Ben Nevis formations (Friend *et al.* 1997; Dallmann and Piepjohn 2020). In addition to the formally described formations, there are also some stratigraphic units of unknown affiliation on the eastern side of the Raudfjorden Trough (Dallmann and Piepjohn 2020).

The Andrée Land Basin contains a 4.5 km-thick post-rift sedimentary succession consisting of sandstones, siltstones and mudstones, as well as subordinate conglomerates and limestones, assigned to the Andrée Land Group (Dallmann and Piepjohn 2020) (Fig. 2). The Andrée Land Group sediments were deposited after the major tectonic movement ceased in the early Devonian, and the group accounts for more than 90% of the Devonian outcrop area (Dallmann 2015). The main part of the succession reflects deposition in a terrestrial basin with extensive alluvial plains and perennial lakes, as well as large meandering and braided river systems entering the basin from the west and south, generally running north towards the basin centre (Moody-Stuart 1966; Friend and Moody-Stuart 1972; Critelli and Reed 1999; Blomeier *et al.* 2003; Dallmann 2015). The Andrée Land Group is subdivided into the Wood Bay, Grey Hoek and Wijde Bay formations. In the southeastern part of the CTSE, in the Dickson Land area, the uppermost part of the Andrée Land Group is referred to as the Mimerdalen Subgroup (Piepjohn and Dallmann 2014). This subgroup, which is of late Givetian–Frasnian or Famennian age, is divided into the Tordalen, Platenryggen and Plantekløfta formations (Piepjohn and Dallmann 2014; Berry and Marshall 2015; Dallmann and Piepjohn 2020). The lower part of the subgroup, the Tordalen Formation, was deposited in terrestrial/fluvial environments periodically influenced by marine ingressions, whereas the coarser-grained, conglomerate-bearing Planteryggen and Plantekløfta formations are interpreted to be syntectonic, terrestrial deposits (Piepjohn and Dallmann 2014). The preservation of lycopsid fossils, which form impressive *in situ* forests in the Plantekløfta Formation, has been attributed to rapid burial in a subsiding, short-lived basin (Berry and Marshall 2015). Provenance studies of the Andrée Land Group sediments indicate a westerly Caledonian source in the Early Devonian, changing to a predominantly eastern–northeastern source in the Middle–Late Devonian, presumably recording uplift of the Ny-Friesland Block along the Billefjorden Fault Zone, as well as influx of sediments derived from an extrabasinal source, possibly reflecting drainage and/or exhumation of Timanian terranes (Critelli and Reed 1999; Anfinson *et al.* 2022).

Magmatism

In Svalbard, late orogenic plutonic processes were active in the Silurian–Early Devonian (Harland *et al.* 1988), with migmatites preserved in NW Spitsbergen and late Caledonian granite plutons found in the western and eastern basement provinces. The largest one, the Hornemanntoppen Granite in the Northwestern Basement Province, yields a U–Pb age of 418 ± 1 Ma (Myhre *et al.* 2008). In Ny-Friesland there are two or more granite plutons, including the Chydeniusbreen Suite, with the well exposed Newtontoppen Granite dated as 430 ± 0.7 Ma (Harland *et al.* 1988; Myhre *et al.* 2008; Dallmann and Piepjohn 2020). Furthermore, in Nordaustlandet there are several late-tectonic Caledonian granite plutons extending along the northern part of the island (Harland *et al.* 1988), where small-size positive magnetic anomalies are located (Fig. 3). Here the Rijpfjorden Granitoid Suite is dated as *c.* 420–410 ± 15 Ma (Johansson *et al.* 2002). Migmatization in the the Duvefjorden Complex, an association of migmatites, granites and gneisses occurring on Nordaustlandet, has been dated as 432 ± 7 and 410 ± 10 Ma, suggesting that partial melting occurred during the last phase of the Caledonian Orogeny (Teben'kov *et al.* 2002; Johansson *et al.* 2004).

In the Early Cretaceous extensive igneous and volcanic activities took place in the High Arctic Large Igneous Province (HALIP). This also included the northern Barents Shelf, where intrusions are seen on regional seismic lines (Lundschien *et al.* 2023), and Svalbard, where radiometric dating of intrusions has given an Aptian age (Corfu *et al.* 2013). Both on Kong Karls Land and on Franz Josef Land basaltic lavas cap underlying Mesozoic strata (Dibner 1998; Olaussen *et al.* 2023). Early Cretaceous magmatic activity (HALIP) is recorded by intrusive basaltic (doleritic) sills in the Cambrian–Ordovician succession and the metamorphic Neo-Proterozoic in the northern part of Ny-Friesland.

Neogene volcanic activities are documented from several locations on northern Svalbard (e.g. Amundsen *et al.* 1988; Skjelkåle *et al.* 1989; Tuchschmid and Spillmann 1992; Treiman 2012). In Andrée Land, several mountains are capped by remnants of 10–12 Myr old (Miocene) basaltic lava flows, which are assigned to the Seidfjellet Formation (Prestvik 1978; Tuchschmid and Spillmann 1992; Dallmann 1999). A rounded intermediate-size positive magnetic anomaly is seen in the mountainous regions of Albert I Land, west of Woodfjorden (Fig. 3). Where preserved, the lava flows, which unconformably cap the Devonian ORS succession of the Andrée Land Basin, reach an accumulative thickness of *c.* 275 m at Seidfjellet (Prestvik 1978; Tuchschmid and Spillmann 1992). The lava flows apparently erupted onto a preglacial peneplane, yet thickness variations indicate that the flows locally filled in low-relief palaeovalleys (Skjelkåle *et al.* 1989; Dallmann 1999, 2015). A subordinate accumulation of similar basaltic lava flows of tentative late Miocene age occurs near Manbreen in Ny-Friesland, possibly suggesting that the Miocene basalt province originally covered a much larger area (Teben'kov and Sirotkin 1990; Dallmann 2015).

Several Quaternary volcanic centres, assigned to the Bockfjorden Volcanic Complex (Dallmann 1999), occur in the Woodfjorden area along a 25 km stretch within a short distance of the north–south-orientated Breibogen Fault, which is a major fault separating Lower Devonian strata (i.e. the Wood Bay Formation) from Proterozoic basement rocks (e.g. Dallmann 2015). The volcanic complex includes a Late Pleistocene (reminiscent) stratovolcano at Sverrefjellet, an Early Pleistocene volcanic neck composed of pyroclastic breccias at Halvdanpiggen and an eruptive centre of uncertain age at Sigurdfjellet, which contains coarse-grained, basaltic pyroclastics penetrated by multiple explosion vents (Amundsen *et al.* 1988; Skjelkåle *et al.* 1989; Treiman 2012). The volcanos are generally composed of alkali basaltic (lithified) pyroclastics, as well as interbedded lava flows and subordinate pillow lavas, all enriched in xenoliths of upper-mantle and deep-crustal origin (Amundsen *et al.* 1987; Skjelkåle *et al.* 1989; Tuchschmid and Spillmann 1992; Treiman 2012).

The tectonic implication of the Miocene lava flows and the Quaternary volcanic centres is debated, and has been linked intermittently to the development of the Yermak Plateau and an associated thermal anomaly, the origin of which is another controversy (e.g. Prestvik 1978; Feden *et al.* 1979; Crane *et al.* 1982; Jackson *et al.* 1984; Amundsen *et al.* 1988; Skjelkåle *et al.* 1989; Okay and Crane 1993; Ritzmann and Jokat 2003; Jokat *et al.* 2016; Kristoffersen *et al.* 2020). The geochemical signature of the Quaternary volcanics is typical of intraplate alkaline volcanism (Amundsen *et al.* 1988), whereas the xenoliths indicate that the Breibogen Fault has a deep-crustal root.

Heat flow

An overview of published heat-flow studies from the Arctic Ocean in the period of 2009–17, including data from the continental margin north of Svalbard, was published by Shephard *et al.* (2018). It has been suggested that the heat-flow anomaly associated with the Yermak Plateau immediately north of the present CTSE reflects an underlying thinned continental crust and magmatism related to the development of the Knipovich and Gakkel ridges, whereas the margin north of Nordaustlandet exhibits low heat-flow values, consistent with an underlying cold crust of either continental or (less likely) very old oceanic origin (e.g. Crane *et al.* 1982; Jackson *et al.* 1984; Okay and Crane 1993; Ritzmann and Jokat 2003; Geissler and Jokat 2004; Jokat *et al.* 2016). There are few onshore heat-flow studies from northern Svalbard. However, this area is known to record a higher heat flow than other parts of the archipelago, expressed by the presence of Quaternary volcanic centres on northern Spitsbergen (e.g. Skjelkåle *et al.* 1989; Tuchschmid and Spillmann 1992; Treiman 2012). Geothermobarometry calculations on xenoliths from the Quaternary volcanic centres in Bockfjorden suggest that the geothermal gradient was very high during the time of eruption and that the continental crust is very thin in the area, possibly *c.* 27 km, which is somewhat thicker than that estimated for the Yermak Plateau (*c.* 20 km: e.g. Jackson *et al.* 1984; Amundsen *et al.* 1988). Based on xenolithic evidence, Amundsen *et al.* (1988) proposed that the Bockfjorden Volcanic Complex is the southern extension of the geothermal heat-flow anomaly associated with the Yermak Plateau and estimated a heat flow of 130 mW m^{-2} for the Bockfjorden area. The same authors suggested temperatures of *c.* 550°C at 7 km depth, corresponding to an average geothermal gradient of 79°C km^{-1}. Collectively, the elevated geotherm, the thinned crust and the intraplate alkaline volcanism are consistent with geologically recent (i.e. Neogene–Quaternary) continental rifting and crustal uplift, possibly caused by a rising mantle plume (Amundsen *et al.* 1988).

Another piece of evidence for elevated heat flow is the occurrence of active thermal springs and associated travertine deposits in the Bockfjorden area (e.g. Banks *et al.* 1997; Salvigsen and Høgvard 1998; Hammer *et al.* 2005; Jamtveit *et al.* 2006). Because the thermal springs are aligned along the Breibogen Fault, and occur several kilometres north and south of the Sverrefjellet stratovolcano, a structural rather than volcanic control has been argued for the high surface heat flow in the area. The springs seem to have been active during most of the Holocene and exhibit mean annual temperatures close to 15°C, occasionally reaching temperatures of up to 28°C (Hoel and Holtedahl 1911; Salvigsen and Høgvard 1998; Jamtveit *et al.* 2006).

Data on pressure regimes are not available but naturally occurring under-pressure is reported from CO_2 research wells drilled onshore southern Svalbard (Olaussen *et al.* 2019; Birchall *et al.* 2020). Moreover, in the offshore parts of the northern Barents Shelf, where there have been some exploration efforts, minor under-pressure (up to 23 bar below hydrostatic pressure) has been observed in the fault-bounded Mesozoic reservoirs of the Fingerdjupet Sub-basin (Birchall *et al.* 2020).

Petroleum geology

Discovered and potential petroleum resources

Exploration for geological resources in the Northern Svalbard CTSE has been limited to some search for metals and industrial minerals (Dallmann 2015; Saalmann 2016). Owing to environmentally protected onshore area and the remoteness of the present CTSE, exploration and the possibility of economic discoveries seem unlikely in the foreseeable future. Recurrent uplift occurring from the Cretaceous onwards throughout the Cenozoic (e.g. Dörr *et al.* 2012) means a high geological risk for hydrocarbon exploration, such as that observed in the southern onshore part of Svalbard (e.g. Olaussen *et al.* 2023).

Current exploration status

There is no commercial exploration activity in the CTSE but several geophysical and geological research projects have been conducted through the years, and some are still ongoing (e.g. universities, NPD and GoNorth: https://www.sintef.no/projectweb/gonorth/).

Hydrocarbon systems and plays

Cambrian and Ordovician bituminous limestones and dolomites (Fortey and Bruton 1973), together with a potential Ordovician calcareous organic-rich source rock (Abay *et al.* 2022), suggest a previous effective petroleum system with primary or secondary migration of hydrocarbons. On Svalbard, south of the present CTSE, and in the SW Barents Sea region, rocks of Neoproterozoic–Devonian age are deeply buried and post-Carboniferous rocks are regarded as the economic basement with respect to exploration for hydrocarbons (Ryseth *et al.* 2021; Tsikalas *et al.* 2021; Olaussen *et al.* 2023). An Ordovician–Lower Devonian petroleum system has, however, been proven in the Timan–Pechora province SE of the Barents Shelf (e.g. Stoupakova *et al.* 2011; Prishchepa *et al.* 2021).

Source rocks

Neoproterozoic. This succession of unmetamorphosed to low-grade metasediments, carbonates, sandstones, shales and tillites is known for well-preserved marine microfloras and organic matter (Knoll 1982*a*, *b*; Knoll and Swett 1985). Notably, recent geochemical analysis of black shales from a *c.* 835–630 Myr old succession in northeastern Svalbard (Kunzmann *et al.* 2015) has revealed that these deposits were dominantly formed under suboxic to anoxic-ferruginous conditions, with shale total organic carbon (TOC) contents reaching up to 2% (Kunzmann *et al.* 2015). However, no additional organic geochemical data are available to form any conclusions on the petroleum potential of these Neoproterozoic deposits.

Cambrian–Ordovician. Bitumen-stained sedimentary rocks assigned to the Lower–Middle Ordovician Valhallfonna Formation on Ny-Friesland have been known for more than half a century (Gobbett and Wilson 1960; Fortey and Bruton 1973; Abay *et al.* 2022). In a recent organic geochemical study, Abay *et al.* (2022) found that Cambrian–Ordovician strata in Ny-Friesland show great variations in TOC content, Rock-Eval data and bulk geochemical data on extracts. The burial depths are uncertain but maturation appears low–moderate and based on T_{max}, the maturities of the investigated samples range from early to peak oil window, corresponding to 0.70–0.85% R_o (Abay *et al.* 2022). In general, there seems to be agreement that biomarkers also indicate a maturity similar to that of T_{max} (Abay *et al.* in prep.). According to the results of Abay *et al.* (2022), the best petroleum source rocks are within the Valhallfonna and Kirtonryggen formations (VF and KF in Fig. 2), which have moderate TOC contents suggesting fair–good source-rock richness. Abay *et al.* (2022) concluded that the relatively high hydrogen index (HI) values in some of the samples are interesting with respect to organic matter quality. While most samples show moderate potential, HI values as high as 424 mgHC g^{-1} TOC at a T_{max} of 444°C suggest very good source-rock intervals for hydrocarbon generation (Abay *et al.* 2022).

New GC-FID and GC-MS chromatograms from the Lower–Middle Ordovician Valhallfonna Formation are presented in Figures 6 and 7. The GC-FID chromatogram represents sample SO-01 in Abay *et al.* (2022) (Fig. 6). The chromatogram is likely to represent migrated petroleum based on the *n*-alkane profile and the huge unresolved complex mixture (UCM) under the *n*-alkanes. The GC-MS chromatograms of extract in sample WP-26 from the Lower–Middle Ordovician Valhallfonna Formation show well-illustrated biomarkers (Fig. 7). The Rock-Eval and TOC data of the exact samples can be found in Abay *et al.* (2022).

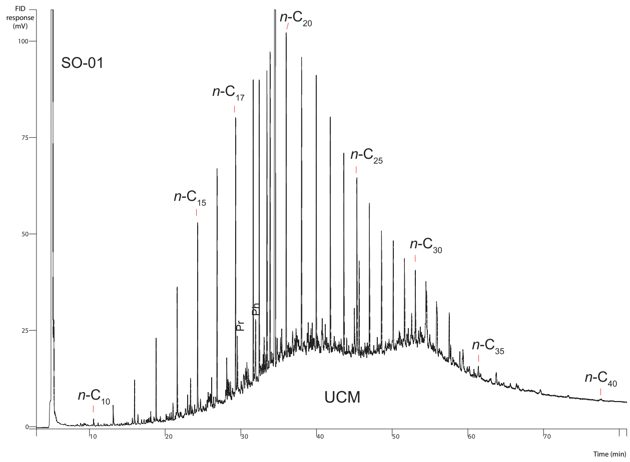

Fig. 6. GC-FID chromatograms of bulk bitumen extracts from the Lower–Middle Ordovician Valhallfonna Formation in Ny Friesland, NE Spitsbergen, showing the peaks of *n*-alkanes with their respective carbon number. Pr, pristane; Ph, phytane; *n*-C_{25}, C_{25} normal alkane. Bitumen extraction from crushed rocks using organic solvents removes low-molecular-weight compounds below *n*-C_{10}–*n*-C_{15} but the presence of a rising baseline and an unresolved complex mixture (UCM) in sample SO-01 indicates some degree of biodegradation, which in turn is likely to suggest the migration of petroleum.

Considering early expulsion of oil from carbonate source rocks, the present Rock-Eval data suggest that the original petroleum generation potential of the Middle Ordovician Kirtonryggen and Valhallfonna formations could have been higher. Biomarker data suggest that some of the extracted bitumen indicates migrated petroleum, as observed from staining on the rock samples. This has implications for determining oil-source rock correlation, which is the ultimate proof of a working petroleum system.

Devonian. To our knowledge comparable detailed organic geochemical analyses have not been carried out in the ORS succession. Harland *et al.* (1988) reported that black mudstones and shales, presumably deposited under euxinic conditions, are locally preserved in the upper part of the Devonian Andrée Land Group (Mimerdalen Subgroup: Piepjohn and Dallmann 2014), although the TOC content of the beds nowhere exceeds 4%. Black shales have also been reported in the 1.1 km-thick Grey Hoek Formation (Dallmann 2015).

Reservoirs. Onshore potential reservoir bodies occur in Proterozoic, Cambrian–Ordovician and Devonian sandstones and carbonates. Apart from the upper part of the Neoproterozoic and the Cambrian–Ordovician successions, previous deeper burial (high temperature) and tectonism have generally transformed the sandstones and carbonate into tight and low-permeability rocks, which, at best, may be classified as unconventional reservoirs. However, this might be an over-simplification due to the limited number of published studies.

Proterozoic. Apart from the upper part of the Neoproterozoic, detailed evaluations (e.g. porosity, permeability, scale and volume) of potential reservoir bodies have not been conducted for the Proterozoic succession. Sandstone- and, particularly, carbonate-dominated facies associations in the Wilsonbreen Formation may hold some, but limited, reservoir potential. Visible porosity occurring in laminated carbonates of the Wilsonbreen Formation, and brecciated carbonates in the same formation, are both candidate fluid-flow units (Fairchild *et al.* 2016*a*, *b*).

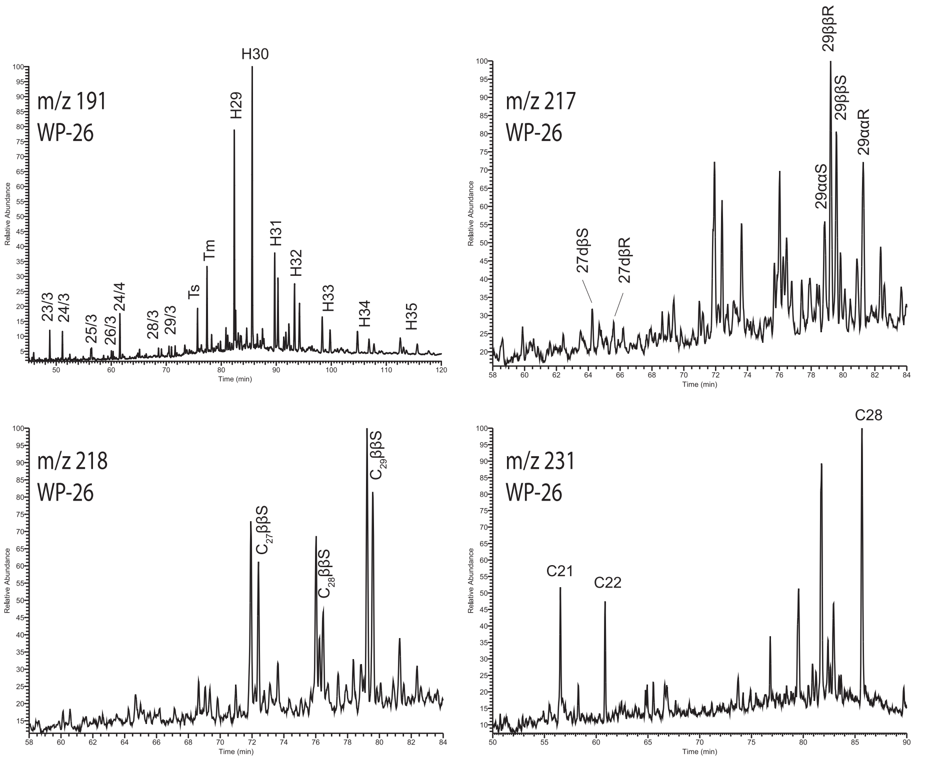

Fig. 7. GC-MS chromatograms of an extract from a sample of the Lower–Middle Ordovician Valhallfonna Formation showing biomarkers, including terpanes (m/z 191), steranes (m/z 217 and 218) and triaromatic steroids (m/z 231). The sample (WP 26) is characterized by laminae and has an HI value of 424 mgHC g^{-1} TOC (Abay *et al.* 2022).

Cambrian–Ordovician. The up to 30 m-thick Cambrian quartz arenites at the base of the Tokammane Formation (Fig. 2), which is a typical Cambrian pipe rock unit, have some visible porosity. The *c.* 640 m-thick Lower Ordovician limestone and dolomite succession shows horizons of vuggy and fracture-related porosity but no detailed porosity and permeability studies have been carried out. However, these units within the Cambrian–Ordovician succession are regarded as a suitable reservoir for oil and gas accumulations.

Devonian. The reservoir potential of any parts of the ORS succession in Svalbard has not been studied in detail. Harland *et al.* (1988) reported that due to calcium carbonate cementation and quartz cementation, the Devonian rocks on northern Spitsbergen generally have low porosity but fractures and faults are locally abundant. Visible porosity has been reported in sandstone bodies interpreted to be meandering fluvial channel fills and lacustrine delta-front deposits within the Andrèe Land Group north of Pyramiden.

Seals. Lateral continuous tabular shale units in both the Ediacaran and Cambrian–Ordovician, as well as in the Devonian, successions are potential conventional seals. Tight carbonate horizons are also effective seals.

Traps. Contractions related to the Caledonian and the Eurekan orogeneses have resulted in large anticlines (Dallmann and Piepjohn 2020). In addition, regional décollement zones may form suitable traps. Potential structural traps should exist in the faulted areas of the Devonian troughs/basins in connection with fractured sandstone reservoir rocks and shaly cover rocks. Stratigraphic or diagentic traps should be present in the older carbonate successions. Trap formation by the emplacement of igneous intrusions, particularly sills, into sedimentary rocks are a well-documented mechanism in many oil-producing volcanic sedimentary basins (e.g. Rohrmann 2007; Senger *et al.* 2017). However, little is known about the occurrence and potential distribution and geometries of the feeder systems of the Neogene lava flows and the Quaternary volcanics of the Northern Svalbard CTSE, although magma emplaced during the latter event clearly penetrated parts of the Devonian succession (Skjelkåle *et al.* 1989).

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Author contributions **MS**: writing – original draft (lead); **SO**: writing – original draft (equal); **M-AD**: writing – original draft (equal); **S-AG**: writing – original draft (equal); **TBA**: formal analysis (equal), investigation (equal), writing – review & editing (equal).

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