On the the origin of the Yermak Plateau north of Svalbard, Arctic Ocean

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- Arctic Ocean
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- Eurekan Orogeny

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The Yermak Plateau north of Spitsbergen and Morris Jesup Spur and rise north of Greenland relate to the Late Cretaceous-early Cenozoic interaction between an independent Greenland plate and the larger North American and European plates. We have recovered 21 new dredge hauls from three locations on the Yermak Plateau with an abundance of metasedimentary and gneissic rocks with strong affinities to known lithologies from northwest Spitsbergen. The continental outlier requires Paleogene dextral shear close to the coast of West Spitsbergen to accommodate opening of the Sophia Basin between the plateau and the continental margin. The postulated large-offset (100–150 km) shear zone (de Geer Fault) is supported by seismic velocity anomalies down to mid-crustal levels, a ubiquitous feature of known large-offset continental transform faults regardless of crustal rock composition. A continental sliver including the Yermak Plateau and Prins Karls Forland initially moved with Greenland along the de Geer Fault during the early Eocene stage of Eurasia Basin opening and facilitated opening of the Sophia Basin north of Spitsbergen by crustal extension. Later offset of the de Geer Fault north of Spitsbergen and formation of the Danskøya Basin in a transfer zone was probably induced by a restraining bend in the Hornsund Fault Zone active at the same time. The 65 km-wide, circular-shaped, northeastern tip of the Yermak Plateau is a young volcanic feature formed between Chron 22 and Chron 18 at the junction between the Gakkel Ridge and the Yermak continental block before separation of the Morris Jesup Spur and Yermak Plateau. The Yermak Plateau became part of the European plate prior to Chron 13 as the Gakkel Ridge propagated into the Northeast Greenland margin and the subsequent dextral motion shifted west to the Hornsund Fault Zone. The de Geer Fault and the Hornsund Fault Zone may have been in existence at the same time.

Introduction

Arctic geoscientific research over the last fifty years has documented a general relationship between the independent Paleogene motion of Greenland and tectonic events in the Canadian Arctic (Eurekan Orogeny) and on Svalbard (West Spitsbergen Thrust and Fold Belt) (Fig. 1). While the geology of the respective land areas has been fairly well explored (CASE Team, 2001; Henriksen, 2005; Dallmann, 2015; Piepjohn et al., 2016), the offshore links are uncertain; in particular, the origin of outlying structures such as the Yermak Plateau north of Svalbard and the Morris Jesup Spur north of Greenland (Fig. 1). It was early recognised that reconstructions of the position of Greenland and the Lomonosov Ridge back to the time of onset of

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Figure 1. Overview of the main submarine features north of Svalbard and Greenland with domains (red and yellow) and major faults (white) of the land geology involved in the early Cenozoic Eureka Orogeny. Bathymetry from Jakobsson et al. (2012), geological information from Svalbard from Dallmann (2015), from Ellesmere Island from Piepjohn et al. (2016) and from North Greenland from Pedersen & Håkanson (1999), von Gosen & Piepjohn (2003) and Svennevig et al. (2016). Abbreviations: EGR – East Greenland Ridge, HR – Hovgard Ridge.

seafloor spreading in the Eurasia Basin produced overlaps if the Morris Jesup Spur and Yermak Plateau were continental fragments (LePichon et al., 1977; Feden et al., 1979; Vogt et al., 1979). In this contribution, we first review the state of knowledge of the relevant tectonic features, report on an extensive effort to dredge known basement outcrops at three sites on the Yermak Plateau and reconsider published crustal velocity information. The objective is to develop a working hypothesis which integrates transform plate motion west of Spitsbergen with the formation of the Sophia Basin and the Yermak Plateau to the north.

Outline of the geological framework

The plateau north of Spitsbergen is named after Yermak, the first icebreaker in the world. Yermak, with is 9000 horsepower, reached up to 81° 21' N during its first season in 1899 (www.prlib.ru/en/history/619672). The plateau (water depth 500–1000 m) has a western NNW-trending part which extends north about 200 km from the shelf break north of Svalbard, and a northeastern part parallel to the Gakkel spreading centre (Figs. 1 & 2). The eastern end (east of 82° 30' N, 14° E) is a circular-shaped, 65 km-wide feature about 500 metres deeper than the adjacent part of the plateau. The northeastern part of the Yermak Plateau is separated from the margin north of Spitsbergen by the Sophia Basin (Fig. 2). The relevant geological framework includes; i) the Yermak Plateau, ii) the Sophia Basin and the continental margin north of Spitsbergen, iii) the West-Spitsbergen Fold and Thrust belt and structures on the continental shelf west of Spitsbergen.

Yermak Plateau

The geophysical results reported by Jokat et al. (2008) and Geissler et al. (2011) show that the smooth and rounded cross-section of the Yermak Plateau is due to sediments which cover basement topography with up to 2 km of elevation differences over a distance of 10–15 km in the northwest (Fig. 3A). Basement in the south forms a large, about 180 km-wide block which becomes narrower (~100 km) and more dissected towards the north. The Sverdrup Bank is part of the high eastern side of this large block and bedrock is exposed at the sea bed in at least two local areas. Another basement exposure is off this block farther to the northeast (Figs. 2, 3B).

The NW-SE-trending western part of Yermak Plateau has received most attention in geophysical studies. Acoustic basement has velocities in the range 5.1–5.8 km/s south of 81° 30' N (Austegard, 1982; Ritzmann & Jokat, 2003) which compare well with compressional velocities (>5 km/s) of the metasedimentary basement rocks on Spitsbergen, albeit the relationship between velocity and petrology is non-unique. Permo–Carboniferous carbonates and evaporites have a similar velocity range >5 km/s with maximum values exceeding 6 km/s (Elverhøi & Grønlie, 1981; Eiken, 1985; Evertsen, 1988). An unreversed seismic refraction line (line 4, Fig. 2) shows velocities of 4.3, 6.0 and 8.0 km/s which was interpreted as a 20 km-thick crust of continental rocks (Jackson et al., 1984). Riefstahl et al. (2013) reported the first effort to dredge basement outcrops on the Yermak Plateau apart from a single gneiss boulder recovered in a dredge of opportunity in the late 1970s (Jackson et al., 1984). More than half of the rocks recovered from a dredge on Sverdrup Bank and another site 25 km to the north (Fig. 2) were magmatic rocks, mostly alkaline basalts. It was concluded that the alkaline dolerites are related to rift magmatism (~51 Ma) and the metamorphic rocks comparable to the Devonian and older basement rocks of northern Spitsbergen (Riefstahl et al., 2013).

The northeastern part of the Yermak Plateau (north of 82° N) is associated with relatively high magnetic amplitudes (up to 1000 nT) which stand out compared to the quiet magnetic field associated with the western and southern part (Jackson et al., 1984; Brozena et al., 2003; Jokat et al., 2008). Several investigators have linked the magnetic anomaly amplitude to a relatively high content of magnetic minerals in volcanic source rocks (Feden et al., 1979; Brozena et al., 2003). A 100 km-long seismic refraction line shot in 1981 (line 3, Fig. 2) to investigate the deeper crustal structure had very sparse spatial shot-point intervals (15–22 km) beyond 50 km offset (Jackson et al., 1984). Nevertheless, the observed amplitudes appeared to match a synthetic seismogram representing an upper 8 km-thick layer of 5.0 km/s velocity over rocks with velocities in the range of 6.7 – 7.2 km/s typical of oceanic layer 3, but thicker. Their preferred interpretation is thickened oceanic crust, in line with the proposal of Feden et al. (1979) and Vogt et al. (1979); the magnetic part of the Yermak Plateau may have been

Figure 2. Overview of locations of seismic profiles and major basement structures north of 79°N. Basement ridges outlined by contours for sediment thickness <1.5 km (brown areas) with data from northwest of Spitsbergen from Eiken (1992) and Opsahl (1997), and data from the Yermak Plateau from Jokat et al. (2008) and Geissler et al. (2011). Dashed white line outlines the northeastern tip of the Yermak Plateau which is suggested to be a volcanic construction. Seismic reflection lines (red) are from Geissler et al. (2011). The crustal transition from continent to ocean (COB) west of Spitsbergen is from Engen et al. (2008), the location of Hornsund Fault Zone from Eiken (1994), Jokat et al. (2008) and Blinova et al. (2009), and the Bouguer gravity gradient (red area) is adapted from Minakov et al. (2012, fig. 6). The simplified geology of Spitsbergen and Nordaustlandet is from Dallmann (2015). Our dredge locations on the Yermak Plateau are shown by white Xs and the seismic refraction profiles (3 and 4) are from Jackson et al. (1984) and shown by heavy black lines. Abbreviations: AWI – Alfred Wegener Institute, Germany, BF – Billefjorden Fault, IF – Isfjorden, KF – Kongsfjorden, LF – Lomfjorden Fault, NBP – Northwestern Basement Province, NFT – New Friesland Terrane, NPD – Norwegian Petroleum Directorate, SB – Sverdrup Bank, PKF – Prins Karls Forland, YBF – Ymerbukta Fault.

Figure 3. (A) Line drawings of seismic profiles across the Yermak Plateau. Data from the northeastern part are from Jokat et al. (1995) and Gjengedal (2004), and from the western part from Geissler et al. (2011). Sediments interpreted as younger than mid-Miocene (Geissler et al., 2011) are shown in green colour and acoustic basement in brown colour. Seismic velocities are in km/sec. The locations of seismic profiles are shown in Fig. 2. (B) Line drawing of composite seismic profiles across the Sophia Basin based on data from Geissler et al. (2011) with the same colour scheme as in Fig. 3A. Abbreviation: MS – Mosby Seamount. Abbreviation: AWI – Alfred Wegener Institute, Germany, ODP – Ocean Drilling Program.

generated by seafloor spreading with excessive outpouring of basalt starting at Chron 20 and reaching a maximum between Chrons 18 and 13. Other investigators favour a northeastern volcanic part generated by high basalt production contemporaneously with formation of the Morris Jesup Rise, and a north-western and southern part of the Yermak Plateau comprising:

- i) thinned continental crust based on crustal seismic velocity structure and magnetic signature (Jackson et al., 1984) or a downfaulted splinter of the Svalbard shelf (Birkenmajer, 1972).
- ii) a transform-related ridge formed by massive intrusions of basalt (post Chron 7) along the western margin to account for high heat flow (Crane et al., 1982, 1988; Okay & Crane, 1993).

A third alternative has been advocated by Jokat et al. (2008) based on the combined seismic reflection and potential field data. They rejected a potential plate boundary between the two parts of the plateau and suggested that the structure is rather a collection of blocks of stretched continental crust formed by a broadening of the Hornsund Fracture Zone in the north. The high intensity of the magnetic field over the northeastern part was considered to be a result of intrusions at depth.

The Sophia Basin and the continental margin north of Spitsbergen

The Sophia Basin constitutes a more than 2000 m-deep reentrant in the continental margin north of Spitsbergen (Figs. 1 & 2). A northeast-trending basement ridge runs along the axis of the basin (Figs. 2 & 3B) and reaches 700 metres above the basin floor in two places (Geissler & Jokat, 2004), but any buried continuity between the two is hitherto unknown. The basement ridge (Mosby Seamount) is flanked to the north by rotated basement blocks (Fig. 3B), and basement to the south is undetected below a thick sediment accumulation which may reach a thickness of 9 km (Geissler & Jokat, 2004). The magnetic field intensity over the deep part of the Sophia Basin has no distinct linear features except for local maxima

Figure 4. The Bouguer gravity field north of Svalbard (figure courtesy of A. Minakov). The direction of initial opening in the Eurasia Basin is shown by the black arrow based on data given by Gaina et al. (2002) and Glebovsky et al. (2006). The dashed white line outlines the northeastern tip of the Yermak Plateau which is suggested to be a volcanic construction.

(Berglar et al., 2016; Jokat et al., 2016). The widest part of basin is related to an offset in the continental slope at 81°N, 17°E north of Hinlopen Strait, accompanied by a steep change in crustal thickness as defined by the Bouguer gravity gradient (red shaded area in Fig. 2). The Bouguer gravity field is obtained by correcting the observed Free Air Gravity values for the density deficit of water with respect to sediments across a continental margin, and the horizontal Bouguer gravity gradient will reflect the slope of the crust–mantle interface. The Bouguer gravity values indicate an abrupt crustal thinning at the northeastern end of the Sophia Basin (Fig. 4). The crust below the basin is interpreted from gravity modelling to be dense, about 5 km thick and oceanic-like (Geissler & Jokat, 2004). The combined geophysical data suggest that the basin is floored by attenuated and heavily intruded continental crust (Geissler & Jokat, 2004; Engen et al., 2008).

The continental basement on the shelf north of Spitsbergen drops by about 1.5 km at the Møffen Fault (Eiken, 1992). Deep seismic data combined with gravity modelling suggest that the continental crust shallows to the north from 24 km to 16 km across the fault and the modelled average density of the crust to the north is higher than below the shelf (Sundvor & Austegard, 1990). Also, Geissler & Jokat (2004) interpret the crust north of the Møffen Fault (Fig. 2) to be part of a continent–ocean transition zone where the crust in the central part of the Sophia Basin is thinned to about 5 km.

The land geology of northern Spitsbergen (north of 79° N) is characterised by a c. 50 km-wide N–S-trending graben filled with Devonian sediments and flanked by two blocks of pre-Caledonian metamorphic rocks (Fig. 2). The bounding, large-scale, N–S-striking faults show mostly strike-slip kinematic features (Dallmann, 2015) and the Devonian ‘Old Red’ sedimentary rocks sit on a crustal-scale extensional detachment with a top-to-the-north displacement of >50 km (Braathen et al., 2017). The rocks of the Northwestern Basement Province (NBP) west of the Devonian graben are dominantly granitic gneisses and schists of Mesoproterozoic or earliest Neoproterozoic age (>960 Ma) later migmatized and intruded by granites during the Caledonian deformation (Pettersen et al., 2009). The Northeastern Basement Province to the east of the Devonian graben includes the Western Ny-Friesland (NFT) and Nordaustlandet terranes (Dallmann, 2015 and references therein). The rocks of the Western Ny-Friesland terrane are Palaeoproterozoic gneisses and Mesoproterozoic metasedimentary rocks deformed during the Caledonian Orogeny while the Mesoproterozoic and Neoproterozoic basement rocks of the Nordaustlandet terrane are metasediments (phyllite, quartzite) and metavolcanics covered by several kilometres of unmetamorphosed sediments (Dallmann, 2015). Permo–Carboniferous carbonate and silicic rocks are present flanking the southern part of the Hinlopen Strait (Fig. 2).

The plate boundary between Greenland and Svalbard

The first continental reconstruction presented by Wegener (1912) sought to minimise the misfit of approximate shelf edge geometries. His proposal implied a straight E–W directed separation between Greenland and Svalbard. At the same time, de Geer (1912, 1919) recognised the need for a large elevated detrital source area west of Spitsbergen to explain the influx of coarse sediment to the Central Basin of Spitsbergen during the early Tertiary. He considered the North Atlantic Ocean north of Iceland to be the result of a sunken landmass which he named the Scandic. During the early Tertiary, the elevated Scandic landmass had shed sediments into the Central Basin of Spitsbergen, but had later subsided while Spitsbergen had become more elevated. de Geer later pointed out a peculiar relationship between the Scandic area and the Arctic Ocean manifested by the co-linear trends of the shelf edge from Norway to north of Spitsbergen with that of the shelf edge north of the Canadian Arctic (de Geer, 1926). Later, Du Toit (1937) considered the co-linear trends of the East Greenland shelf edge and the shelf edge north of Svalbard. De Toit’s idea would imply a predominant component of shear between Greenland and Svalbard, but he did not pursue the implications in any detail. Instead, Wegmann (1948) picked up on de Geer’s thoughts and recognised a trend he named the de Geer Line

Figure 5. Compilation of seismic data across the graben structure along the coast of West Spitsbergen. The seismic data are from Eiken (1994), Blinova et al. (2009) and Gabrielsen et al. (1992) and the structural data south of Sørkapp from Bergh & Grogan (2003). Basement ridges NW of Spitsbergen as in Fig. 2. The location of the Hornsund Fault is from Eiken (1994) and Jokat et al. (2008) and the continent-ocean crustal boundary from Engen et al. (2008). Abbreviations: PKL – Prins Karls Forland, SEDL – Svartfjella, Eidembukta and Daumannsodden Lineament, SJF – St. Jons Fjorden, YBF – Ymer Bukta Fault.

represented by a small circle on the globe. By backtracking the relative motion between Greenland and Svalbard parallel to this small circle, the mountains of northeast Greenland and northern Ellesmere Island would return to an initial position off the coast of Spitsbergen. This scenario would explain the

early Tertiary Scandic land area of de Geer (1926). Wilson (1965) associated the de Geer Line with a dextral transform fault which has been referred to by many authors as the “de Geer Shear Zone”. We use the term ‘de Geer Fault’ for a postulated major dextral transform close to the coast of West Spitsbergen with active displacement during formation of the Sophia Basin in the Paleocene–early Eocene (Fig. 2).

The main tectonic structures along the continental shelf west of West Spitsbergen are a near-shore graben and the Hornsund Fault Zone (Fig. 5). The graben is 15–20 km wide and appears to open up north of 79° N, but its southern continuation is unclear (Bergh & Grogan, 2003). The main graben boundary fault changes polarity between Isfjorden and Bellsund (Fig. 5) and is filled with 1–2 km of weakly deformed sediments (Blinova et al., 2009). A drillhole in Forlandsundet (Fig. 5, star symbol) reached metamorphic basement at 1.05 km. Kleinspehn & Teyssier (2016) suggested that the Forlandsundet graben was part of a broader piggy-back basin within the active West Spitsbergen Fold and Thrust Belt and the oldest graben sediments were deposited during the late Eocene (after 38 Ma). The main graben formation came later in the early Oligocene.

The Hornsund Fault was first detected in single-channel seismic data and sonobuoy measurements on the outer shelf from Bear Island to Hornsund (77° N). It was characterised by a province of high seismic velocities (3.8–4.2 km/s) at the sea bed to the east and a wedge of low-velocity sediments (1.7–1.8 km/s) below the upper continental slope to the west (Sundvor & Eldholm, 1976). The boundary between shallow basement and the depositional wedge was named the Hornsund Fault. The feature was later extended to 79° N (Schluter & Hinz, 1978; Sundvor et al., 1978; Myhre et al., 1982) and farther north by Jokat et al. (2008). Subsequent surveys between Bear Island and the southern tip of Spitsbergen revealed an up to 50 km-wide fault complex where the listric eastern master fault (Knølegga Fault) has a throw of >3 km (Gabrielsen et al., 1990; Rehman, 2012). The fault complex appears to terminate just south of 76° N and its NNW-ward extension is unclear (Bergh & Grogan, 2003). The subsurface structure below the continental shelf north of 76° 30' N is poorly surveyed. The position of the Hornsund Fault used in most publications is not a distinct master fault, but the eastern fault of a >20 km-wide, complex, coast-parallel zone of down-dropped blocks to the west (Schluter and Hinz, 1978; Eiken & Austegard, 1987; Eldholm et al., 1987; Eiken, 1994; Bergh & Grogan, 2003; Faleide et al., 2008; Blinova et al., 2009; Faleide et al., 2010). Jokat et al. (2008) suggested a northward extension to 81° 30' N (Fig. 2). The Hornsund Fault does not represent the boundary between continental and oceanic crust west of Spitsbergen as Breivik et al. (1999) have used the Bouguer gravity calibrated by seismic velocity data to outline the crustal transition from continent to ocean to within a zone of 20 km width west of Spitsbergen (Figs. 2 & 5). The implication is that up to 40 km of extended continental crust may be present in a transtensional transition zone between the Hornsund Fault and the inferred boundary between continental and oceanic crust. We use the term ‘Hornsund Fault Zone’ for this transition zone.

Materials and methods

We have used a hovercraft research platform (Kristoffersen & Hall, 2014) to recover a total of 14 successful rock dredges from two groups of localities separated by ~15 km in a north-south direction on Sverdrup Bank and one group of 7 dredges from a site on the northeastern part of the plateau (Figs. 2 & 6). The total amount of material weighs 103 kilos and includes 269 rock specimens. Four attempts to recover rocks from the western side of Sverdrup Bank were unsuccessful. Dredging was carried out while moving with the drifting sea ice from an initial position upstream of the target. We monitored the seabed conditions using a 12 kHz echo sounder and single-channel seismic reflection measurements with energy from a 0.3 litre air-gun source. A few of the dredged rock specimens had clean broken surfaces.

Figure 6. Left: Locations of dredge hauls on the Yermak Plateau indicated by track segments of different colours with the oval marking the area of maximum recovery on Sverdrup Bank. Right: Distribution of the lithologies in the different dredge hauls and proposed ages based on similarities with the lithology of rocks from northwestern Spitsbergen. Note that orthogneisses may also be of Caledonian age (e.g., Petterson et al., 2009).

Sverdrup Bank

The highest part of the Sverdrup Bank is bevelled with a slightly elevated western rim (Figs. 2 & 6, bottom). The opaque acoustic character of the high is interpreted as basement outcrop and weak internal reflections have a northeast component of dip (Geissler et al., 2011). A small prograding wedge of sediments is present on the southwest side of the high (Fig. 6, bottom), but such a wedge is not apparent on the western and northwestern sides (Geissler et al., 2011). The dredging operation was concentrated over the high on the eastern rim (Fig. 6). In one instance the dredge fastened on the bottom and the kevlar line (breaking strength 2.8 ton) parted.

The results presented in Table 1 and Fig. 6 (right side) show more than 60% (63% and 84%) of the rock specimens recovered from the Sverdrup Bank to be metamorphic lithologies followed by sediments (13% and 23%) and igneous lithologies (3% and 13%). At the main site on the bank (81° 26' N), metasedimentary rocks including phyllites, are the dominant (63%) rock type with subordinate gneissic rocks of both igneous (orthogneisses) and sedimentary (paragneisses) origin. Migmatites and granites are absent. The igneous rocks (13%) are exclusively holocrystalline basaltic rocks. The sediments (23%) are dominantly siliceous and calcareous rocks, in places with fossils, while red sandstone samples are subordinate.

Table 1. Summary of bulk lithologies recovered in the dredges from Sverdrup Bank (14) and Northern Basement High (7). The results of Riefstahl et al. (2013) from a single dredge given in parenthesis.

Lithology	Sverdrup Bank			Northern Basement High
	North	South	*West	
Sediments	23%	13%	(30%)*	53% (0%)
Igneous rocks	13%	3%	(63%)*	24% (60%)
Metamorphics	63%	84%	(7%)*	20% (40%)

*results of Riefstahl et al. (2013).

At the southern site of Sverdrup Bank (81° 19'N), the metamorphic rocks (84%) include phyllites, migmatites, orthogneisses, paragneisses and amphibolites while metasedimentary rocks are subordinate. The igneous contribution is represented by a single angular basalt fragment with a dark fine-grained matrix and a moderate content of biotite flakes. The few lithified sediment samples (13%) are partly terrestrial, moderately sorted sandstones and partly siliceous and calcareous rocks. Thin-sections from seven of the samples were studied and the results will be discussed as part of the interpretation.

Northeastern Basement High

The successful dredge hauls and seismic reflection measurements define a 4.5 km-long and 1 km-wide, E–W-trending, bedrock outcrop at the seabed (Fig. 6) at a location termed the Northern Basement High of Riefstahl et al. (2013). The range of recovered lithologies includes a plate fragment of bedded black shale with plant fragments, silicified limestone, chert and a reduced abundance (20%) of metamorphic rocks (Fig. 6, upper right). Dredge # 10 (not shown in Fig. 6) became temporarily stuck on the seabed but eventually recovered large fragments of basalts with fresh broken surfaces comprising 24% of all dredged material recovered at the site. The basalts are holocrystalline with prismatic plagioclase. Hornblende and pyroxene are visible to the eye and no recrystallisation features are observed.

Interpretation

In situ material or not?

The level top surface of the Sverdrup Bank and exposure of basement are most likely due to erosion by deep draft icebergs and/or ice shelves through the Pleistocene (Kristoffersen et al., 2004; Gebhardt et al., 2011). Moving ice resting on bedrock plucks off material and moves debris in a basal zone where isometric shapes rotate more easily and lead to greater abrasion and more equidimensional debris which quickly attains a sub-angular roundness mode (Boulton, 1978; Bennett et al., 1997). Clast shape is influenced by the lithology for rocks with a distinct foliation whereas blocky samples are more robust (Bennett et al., 1997).

Rocks recovered by dredging always raise the question of genuine in situ representation. All successful dredge hauls recovered from the Sverdrup Bank had broadly similar relative representation of litho-

logies and metamorphic assemblages were dominant with no exceptions (Fig. 6, right panel). The eleven attempts to dredge on the eastern perimeter of the bank swept over an area of more than 40 square kilometres and the recovery from each deployment ranged from 0 (2 hauls) to more than 15 (3 hauls) rock samples. Maximum recovery was narrowed down to a 5 km-long and 1.5 km-wide NW-trending area where also one dredge got stuck and was lost (Fig. 6). All three short dredge hauls at the southern site on Svalbard Bank were successful (10–16 samples). The local character of rock concentration on the seabed is also illustrated by the fact that four attempts to dredge on the western slope of Sverdrup Bank covering a distance of 13 kilometres were unsuccessful except for a single gneiss sample (Fig. 6, dredges 11–14/2011). The dredge site of Riefstahl et al. (2013) is within a kilometre of where one of these unsuccessful attempts was terminated (Fig. 6).

On the Northern Basement High, we had maximum rock recovery at a basement ridge also documented from multibeam bathymetry by Riefstahl et al. (2013).

If we classify the shapes of our rock samples into four categories; well-rounded, rounded, sub-angular and angular, an average of 13% of the rocks from Yermak Plateau may be categorised as rounded (Fig. 7, lower panel). No well-rounded specimens are present. Out of curiosity for some reference, we recovered a test dredge in the glacial wedge within the slide scar NNW of the Hinlopen Strait and found rounded rock specimens in 34% of the recovery (Figs. 2 & 7, lowermost site). Angular rock samples from the two

Figure 7. Upper: Examples of dredge hauls from each of the three sites. Lower: Assessment of roundness of the recovered rocks in some of the dredges.

northern sites on the Yermak Plateau are generally twice as abundant as the shapes of clasts entrained in the same glacial sediment wedge mentioned above. In particular, we note a platy rock specimen in one dredge (4–2010) on Sverdrup Bank (Fig. 7, upper panel). The southern site on Sverdrup Bank, however, has a relatively low abundance of angular shapes, but the sum of angular and sub-angular shapes is just as high as at the two other sites to the north (Fig. 7, lower panel).

Another aspect is repeated recovery. Dolerite rock samples are present in all dredges from the main Sverdrup Bank which strongly suggests proximity to a local source rather than random glacial erratics.

Two of the specimens recovered from the main Sverdrup Bank outcrop were considered ‘exotic’ rocks (Fig. 6). Thin-sections of these samples reveal a medium-grained, weakly schistose calcareous schist where centimetre-long radial bundles of wollastonite overgrow the elongate calcite grains. Although this lithology has no known analogue in the geology of northern Svalbard or Nordaustlandet, we note that the samples were recovered in two different dredge hauls and therefore may be less ‘exotic’ than originally thought. We conclude that a contribution from ice-rafted material may be present in the rock populations recovered from the Sverdrup Bank, but not of any magnitude which could significantly influence our conclusions.

Table 2. List of the main lithologies in the dredged material and proposed interpretation based on equivalents from the geology of Spitsbergen (Dallmann, 2015).

Lithological characteristics	Interpretation
Cryptocrystalline, vesicular volcanic rocks, porous light texture,	Recent volcanics? prismatic micro-phenocrysts visible, origin <200 m water depth
Sediments, soft clastic, often terrestrial	Cenozoic sediments?
Lithified shales and sandstones	Mesozoic sediments
Holocrystalline basaltic rocks w/doleritic texture	Mesozoic volcanics?
Hard calcareous and siliceous sediments (cherts), calc. fossils	Replaced by red-coloured siliceous Perm–Carb. sediments
Red terrestrial sandstone	Devonian sediments
Phyllites; shaly metasediments with strong cleavages	Pre–Caledonian sedimentary rocks?
Crystalline schists; recrystallised metased. and igneous rocks	Pre–Caledonian rocks?
Quartzites; recrystallised siliceous sediments	Pre–Caledonian rocks?
Migmatites; heterogeneous granitic and gneissose rocks	Caledonian or pre–Cal. rocks?
Amphibolites; metamorphosed igneous rocks	Pre–Caledonian rocks?
Paragneisses; coarse-grained gneisses of sedimentary origin	Pre–Caledonian rocks?
Orthogneisses; coarse-grained gneisses of metamorphosed rocks	Caledonian or pre–Cal.?
Exotic rocks; rocks not encountered so far in Svalbard geology	??

Sverdrup Bank: geological interpretation of dredged material

The second author has made a qualitative visual assessment of each rock specimen in the total inventory of 269 samples based on a personal knowledge base gained from more than twenty seasons of geological field mapping of the basement rocks of Spitsbergen and Nordaustlandet (Fig. 2). Thin-sections were made from 17 samples for closer inspection. The samples were grouped following the criteria given in Table 2.

Basement in northern Svalbard reflects the superposition of three orogenic events; middle Mesoproterozoic (1900 Ma), Early Neoproterozoic (Grenvillian, 900 Ma) and the Caledonian event (450 Ma). This makes it impossible to associate a particular metamorphic event with individual rock samples. However, rocks deformed during the Caledonian event have a single preferred orientation of metamorphic textures and post-tectonic intrusions show homogeneous igneous texture; rocks older than the Caledonian event have polymetamorphic textures and granitic rocks were deformed into granitic gneisses and augen gneisses, while basic rocks were transformed into amphibolites.

The recovery from Sverdrup Bank is dominated by metamorphic rocks at both sites (Fig. 6). Calcareous and silicic sedimentary rocks are represented by 15% of the samples while only a single plate-shaped sample of red sandstone is present. Dolerite makes up about 15% of the total recovery. This suggests an outcrop of metamorphic basement of continental crust and the lithologies have a strong affinity to those of the geology of northern Svalbard about 200 km to the south. The bank is the emergent part of a large crustal block (Fig. 3A) located within the domain of subdued magnetic field variations which suggests that the entire southern and northwestern part of the Yermak Plateau is part of a continental crustal structure (Feden et al., 1979; Jackson et al., 1984; Jokat et al., 2008).

Sedimentary rocks (53%) dominate the recovery at the Northern Basement High on the Yermak Plateau where the metamorphic contribution is reduced to 20% (Fig. 6). This implies that some of the cover rocks above metamorphic basement are retained at this location and the presence of volcanic rocks (24%) is significant.

Discussion

Yermak Plateau – a continental outlier

Our successful dredge hauls from the top of the Sverdrup Bank traversed a more than 40 square kilometre area and returned internally consistent lithological representations (Fig. 6). As shown in Table 1, our results contrast with the relative abundances recovered by a single dredge in each area reported by Riefstahl et al. (2013). Most notably is a scarcity of metamorphic rocks (7% vs. our 63–84%) and abundance of igneous rocks (63% vs. our 3–13%) in the dredges recovered by Riefstahl et al. (2013) from the Sverdrup Bank. Also, the complete lack of consolidated sediments (0% vs. our 53%) in their dredge from the Northern Basement High. All our recovered lithologies have analogues in the geology of northern Spitsbergen and we consider the contrasting abundances in our dredge hauls to reflect local geological differences in acoustic basement. The combined results provide documentation for the southern and northwestern parts of the Yermak Plateau being an outlier of continental crust which extends about 150–200 km north of the projected straight, WSW–ENE-trending, Eurasia Basin margin of the northern Barents Sea (Figs. 1 & 2).

The continental rocks on Yermak Plateau are separated from the continental margin north of Spitsbergen by the deep-water embayment which forms the Sophia Basin (Fig. 2). The gravity data

suggest the basin is floored by a high-density (2.9 g/cm^3) crust interpreted as extended and intruded continental rocks (Geissler & Jokat, 2004). If the Sophia Basin formed by crustal extension, we need to consider at least two issues:

i) First, an overlap arises between the northeastern tip of Yermak Plateau and the continental margin north of Nordaustlandet if we close the Sophia Basin by back-tracking the present northeast-trending part of the plateau along a direction either parallel to the postulated de Geer Fault or the initial opening of the Eurasian Basin (Fig. 2).

ii) Secondly, a plate geometry which facilitates opening of the Sophia Basin requires initial dextral shear motion along the west coast of Spitsbergen through Forlandsundet on the order of 100–150 km. This offset range is estimated from the separation of acoustic basement of the plateau from an uncertain basement configuration of the continental margin north of Spitsbergen (Fig. 3B) and assuming that extension in the deep basin was compensated by thinning of continental crust and intrusions. We use an offset range because of the uncertain constraints on acoustic basement north of Spitsbergen and the crust below the Sophia Basin.

The circular structure of the northeasternmost tip of Yermak Plateau presents an apparent enigma unless we postulate the feature to be a younger post-rift structure, possibly constructed by volcanism between Chron 22 and Chron 18 based on the age of the adjacent oceanic crust. South-dipping reflections and seismic velocities ($>3.2 \text{ km/s}$) of the acoustic basement (Fig. 3A), as well as a partial magnetic anomaly signature (Jokat et al., 2008), may be circumstantial evidence for the northeasternmost part of the plateau being a volcanic wedge.

The startling lack of exposures of major strike-slip faults along the west coast of Spitsbergen parallel to the relative plate motion has long remained a puzzle (Craddock et al., 1985; Dallmann et al., 1988; Maher & Craddock, 1988; CASE Team, 2001; Dallmann, 2015). Exceptions are the $>70 \text{ km}$ -long Svartfjella, Eidembukta and Daudmannsodden lineaments NW of Isfjorden (Fig. 5) with several kilometres of offset (Maher et al., 1997). The proposed solution to the conundrum is decoupling of stresses in the brittle upper crust between a normal component creating the fold-and-thrust belt and a tangential component responsible for simple shear motion in a proposed zone off the coast of West Spitsbergen (Maher & Craddock, 1988; Nøttvedt et al., 1988). Geological field studies of partitioning of slip in the upper crust along obliquely convergent plate boundaries have been published by Lee et al. (1998), McCaffrey et al. (2000) and Shuanggen (2013), and the spatial scale over which partitioning often occurs is documented by geodetic and seismic networks (Lettis & Hanson, 1991; Wdowinski et al., 2001). Strain partitioning requires anisotropic rocks (Jones and Tanner, 1995).

An initial dextral fault off the coast of West Spitsbergen – the de Geer Fault?

If the Hornsund Fault Zone indeed represented the early Cenozoic strike-slip plate boundary between Svalbard and Greenland, the crustal extension in the Sophia Basin should have propagated westwards to meet the fault and isolated the Yermak Plateau as a continental fragment to the north (Figs. 2 & 8). Instead, the Sophia Basin is terminated to the west by NNW-trending basement ridges which continue north from Spitsbergen. From this, we infer that the eastern flank of the largest basement ridge on the southern Yermak Plateau (Fig. 2) must have represented the plate boundary at the time and was connected to the south to a coast-parallel transform fault (de Geer Fault) which due to later deformation was offset by a transfer zone (Ritzmann & Jokat, 2003) now occupied by the Danskøya Basin (Fig. 2). We present a new geophysical argument for the past existence of the de Geer Fault

Figure 8. Compilations of published seismic velocity distributions in the continental crust along transects across the margin west of Spitsbergen. The data are from seismic refraction experiments using ocean bottom seismometers. The transect at 75° 30'N is from Brevik et al. (2003), transect Hornsund from Ljones et al. (2004), transect Bellsund from Ritzmann et al. (2002), the transect Prins Karls Forland North from Ritzmann et al. (2004), from 79°45'N from Czuba et al. (1999) and from NW Spitsbergen North from Ritzmann & Jokat (2003).

based on the fact that major strike-slip faults in the continental crust are associated with a geophysically defined fault damage zone roughly proportional to the fault length and/or displacement of the fault (Ben-Zion & Sammis, 2003; Faulkner et al., 2003; Sibson, 2003; Mooney et al., 2007). The geophysical signature of the damage zone extends to at least 3–5 km depth, and is associated with 20–50% lower seismic velocity than the neighbouring rocks regardless of crustal rock composition (Ben-Zion et al., 2007; Mooney et al., 2007).

Published transects of the seismic velocity distribution in the crust offshore West Spitsbergen all show significant velocity perturbations in the upper brittle crust (Fig. 8). All investigators interpret these deep velocity anomalies as domains of intense faulting (Ritzmann et al., 2002; Breivik et al., 2003; Ritzmann

and Jokat, 2003; Ljones et al., 2004; Ritzmann et al., 2004; Czuba et al., 2005). The perturbation north of Spitsbergen below the Danskøya Basin is considered to represent a south-plunging crustal-scale detachment (Ritzmann & Jokat, 2003), and to the west (Fig. 8, Transect 79° 45' N) an old transform zone is manifested as a ~1 km/s seaward velocity increase at mid-crustal level (Czuba et al., 2008). Lower velocities are associated with a <20 km-wide zone down to 15 km depth in the Prins Karls Forland North and Bellsund transects, while the Hornsund transect shows a graben underlain by a high-velocity ridge reaching 5 km depth (Figs. 8 & 9). To the south of Spitsbergen (75° 30' N), the coast-parallel trend of crustal velocity perturbations merges with the Hornsund Fault Zone and the continent-ocean boundary (Fig. 8).

We suggest that the significant variations in seismic velocities in the upper crust along the coast of West Spitsbergen landward of the Hornsund Fault Zone compare with other large-offset strike-slip environments and support past strain-partitioned, orogen-parallel dextral displacements along the coast of Spitsbergen of a magnitude not hitherto considered (Maher & Craddock, 1988; Nøttvedt et al., 1988; Morris, 1989; Gabrielsen et al., 1992; Dallmann et al., 1993; Ohta et al., 1995; Maher et al., 1997; Kleinsphen & Teyssier, 2016). Also, this coast-parallel shear motion satisfies a plate boundary geometry which allows for opening of the Sophia Basin, because the basin is bypassed to the west by activity along the Hornsund Fault Zone (Fig. 2). We note, however, that the shear motion associated with the opening of the Sophia Basin (100–150 km) roughly 2/3 half of the predicted relative motion (200 km)

Figure 9. A comparison of the seismic velocity distribution in the continental crust in the transect across the continental margin west of Svalbard north of Prins Karls Forland (upper panel) and Bellsund (lower panel) with the velocity distribution in the crust across major continental strike-slip boundaries such as the San Andreas Fault and the Dead Sea Transform Fault. Data from north of Prins Karls Forland from Ritzmann et al. (2004), from Bellsund from Ritzmann et al. (2002), from the San Andreas Fault from Murphy et al. (2010) and Wallace (1991), from the Dead Sea Transform from ten Brink et al. (2006) and DESERT Group (2004). Abbreviations: CF – Clearwater Fault, SAF – San Andreas Fault, SFF – San Francisquito Fault.

between Greenland and Svalbard during the seven million year time span between Chron 24 and Chron 21 (Fig. 10). Further displacement must have bypassed the basin and occurred farther west along the Hornsund Fault Zone (Fig. 2). Continued activity on the de Geer Fault was possible if the fault continued north across the Yermak Plateau to link up with the Ellesmere domain (Fig. 12).

Figure 10. A compilation of plate motion parameters relevant to early Cenozoic tectonic events north of Svalbard and Greenland. Spreading half-rates and the direction of opening in the Norwegian–Greenland Sea keeping Europe fixed are from Gaina et al. (2019). The spreading rates from the Labrador Sea published by Roest & Srivastava (1989) and Kristoffersen & Talwani (1977) are corrected for the difference relative to the geomagnetic time scale of Gradstein et al. (2012) used here. The stratigraphy of the Central Basin is from Dallmann (2015) and from the Forlandsundet basin from Kleinspehn & Teyssier (2016).

Plate interaction north of Greenland and Svalbard – the state of knowledge

The overlap created by the Yermak Plateau and Morris Jesup Rise evident in early reconstructions (LePichon et al., 1977; Feden et al., 1979) of the Eurasia Basin has remained a puzzle and recent plate tectonic models are vague with respect to details of Paleogene tectonic scenarios north of Svalbard and Greenland (Fig. 11). Minakov et al. (2012) focus on explanations for a relatively narrow (c. 100 km) transition between the point of rapid thinning of the continental crust at the margins of the

Figure 11. An overview of published early Cenozoic reconstructions for the area north of Svalbard and Greenland. Note that the reconstructions are for slightly different times; Minakov et al (2012) for 53 Ma (Chron 24), Døssing et al. (2014) for 45 Ma (Chron 21), Gion et al. (2017) for 50 Ma (Chron 23) and Piepjohn et al. (2016) for 47 Ma (Chron 21).

Eurasia Basin as determined by the horizontal gradient in the Bouguer gravity field and oceanic crust associated with the first identifiable magnetic isochron (Chron 24). Little attention is given to events which involved the crustal domain north of Greenland and Svalbard (Fig. 11, panel A). Similarly, Døssing et al. (2013b and 2014) leave out the details of the Yermak Plateau and Morris Jesup Spur and rise in their reconstructions of the Eurasia Basin north of Greenland (Fig. 11, panel B). A gravity low north of Greenland highlighted by Brozena et al. (2003) as a loading effect generated by crustal shortening is also postulated by Døssing et al. (2014) to relate to a Lincoln Sea – Klenova Valley Fault Zone (LKFZ). The fault zone extends from the western Lincoln Sea shelf and passes eastwards at the foot of the slope north of the Morris Jesup rise and spur (Fig. 11, panel B). The LKFZ projects the domain of Eurekan deformation from the southern boundary of the Pearya terrane offshore, and the Morris Jesup structure is interpreted as a volcanic province formed on an extended continental margin during peak-Eurekan

Figure 12 (A) Reconstruction of the Lomonosov Ridge (North American plate; NAM) at Chron 25 (56 Ma) and Greenland (GRN) relative to Svalbard (European plate fixed; EUR) at Chron 24 using Gplates software (www.gplates.org) and the rotation parameters from Gaina et al., (2002) and Barnett-Moore et al. (2016), respectively. The conceptual outline of tectonic blocks on Ellesmere Island involved in the Eurekan Orogeny (brown colour) are adapted from Piepjohn et al. (2016). Active faults shown by red colour. (B) Reconstruction for Chron 21 (47 Ma.) using parameters from Gaina et al. (2002) for the rotation of North America relative to Europe and from Gaina et al., (2009) for Greenland relative to Europe. Proposed plate boundary connection between the Gakkel spreading centre and the northern end of the Hornsund Fault Zone from the end of opening of the Sophia Basin (Chron 22) to Chron 13 is shown by black lines. (C) Reconstruction for Chron 13 (34 Ma) using rotation parameters from Gaina et al. (2002) for the rotation of North America relative to Europe and from Gaina et al., (2009) for Greenland relative to Europe. Extent of volcanism which formed the northeastern end of Yermak Plateau and the end of Morris Jesup Spur is outlined by the white area.

deformation. So far, no seismic reflection data are available to document the postulated LKFZ. Gion et al. (2017) evaluated previous reconstructions of the Eurekan Orogeny, but offer little detail beyond the statement that crustal material comprising the Morris Jessup Rise and Spur and the Yermak Plateau originated to the east-southeast of Ellesmere Island (Fig. 11, panel C). Piepjohn et al. (2016) have summed up more than two decades of fieldwork on Spitsbergen and Ellesmere Island to explore the constraints from the land geology on the complex tectonic interaction between the Greenland, European and North American plates during the Eurekan Orogeny. The geology of Ellesmere Island comprises a number of tectonic domains bounded by major faults where the direction of motion may have shifted during the orogeny. Their reconstruction for Chron 21 and the sense of fault motion between chrons 24 and 21 (Eurekan Stage 1) along the major faults is shown in Fig. 11, panel D. We note their position of Greenland derived from the rotation parameters of Srivastava & Tapscott (1986) is about 100 km to the south relative to Spitsbergen when compared to more recent plate rotation parameters, e.g., Gaina et al. (2009). In Ellesmere Island, motion on the major faults was sinistral during Stage 1. Subsequently, as the motion of Greenland represented a more direct compression relative to Ellesmere Island, thrusting became predominant and the main faults reversed to dextral motion. Any correlation of the Eurekan deformation zones from Ellesmere Island to Svalbard is difficult at this stage (Fig. 11, panel D). The published parameters for the motion of Greenland relative to Svalbard and the Cenozoic stratigraphy of West Spitsbergen are summed up in Fig. 10. The work of Gaina et al. (2019) suggests that the seafloor spreading direction (shaded blue area) was slightly oblique to the trend of the De Geer Fault (black stippled line) during the late early Eocene (Chron 24 – 21) and possibly also during the late Eocene (Fig. 10). The predicted plate motion has a component of about 40 km perpendicular to the fold belt during the early Eocene and more than 500 km parallel to the fold and thrust belt during the entire Eocene epoch.

On land, the shortening estimates usually involve restoration of part of the stack of thrust sheets and undetected deep thrusts would increase the estimates in all cases. Large values (51–60%) of relative shortening are reported by Saalman & Thiedig (2002) from the Kongsfjorden area (Fig. 5) or 40 km by Lyberis & Manby (1993). Extensive shortening (>42%) documented along the inner part of St. Jonsfjorden (Fig. 5) amounts to about 13 km (Welbon & Maher, 1992), and Bergh et al. (1997) estimated 45% shortening over a 13 km section north of Isfjorden to be a minimum of 20 km. South of Bellsund (Fig. 5), the shortening is 8 km over a 5 km section (von Gosen & Piepjohn, 2001) and >8 km across the fold belt in the Hornsund (Fig. 5) area (Dallmann, 1992). In summary, there appears to be reasonable agreement between the predicted and observed magnitudes of contraction across the West Spitsbergen Fold and Thrust Belt. However, the sum of strike-slip components observed from the land geology are more than an order of magnitude short of the value predicted from plate motion. We have argued for a coast-parallel major dislocation (de Geer Fault) with an offset of 100–150 km required for opening of the Sophia Basin (Figs. 2 & 12). Continued relative motion between Greenland and Svalbard bypassed the Sophia Basin either by northward continuation of the de Geer Fault and/or motion along the a proto-Hornsund Fault Zone to the west (Fig. 2).

Following Srivastava & Tapscott (1986) and Gaina et al. (2002), we assume the Lomonosov Ridge and the Pearya terrane were part of the North American plate during opening of the Eurasia Basin (Fig. 12). Since a significant tract of crust is present in the Eurasia Basin between Chron 24 and the continent-ocean transition as defined from gravity and seismic data along the Eurasia Basin margins (Jackson and Gunnarson, 1990; fig. 3 of Glebovsky et al., 2006; Chernykh & Krylov, 2011; Minakov et al., 2012), we assume an initial opening at Chron 25 (56 Ma.). Using the GPlates software (www.gplates.org), we keep Europe fixed and reconstruct the relative position of the Lomonosov Ridge at the time of Chron 25y (56 Ma) using the finite rotation of Gaina et al. (2002) and the position of Greenland relative to Svalbard at continental break-up using the rotation parameters given by Barnett-Moore et al. (2016). In addition, we move Yermak Plateau along the trend of the de Geer Fault to close the Sophia Basin. The plateau is moved along with a narrow continental block along the west coast of Spitsbergen bounded by the de

Geer Fault to the east and by the Hornsund Fault Zone to the west. The conceptual configuration of an ensemble of crustal blocks which constitute Ellesmere Island is adapted from Piepjohn et al. (2016). The reconstructed relative three-plate configuration at 56 Ma shown in Fig. 12 (upper panel) invites several possible relationships:

- i) A magnetic trend co-linear with the Mt. Rawlinson Fault at the southeastern end of the Pearya Terrane (Jokat et al., 2016) projects eastward across the Lincoln Sea continental shelf towards an offset at the continental margin north of Nordaustlandet (Fig. 12). The linking trend may suggest a continuous fault trace. Alternatively, the Mt. Rawlinson Fault may be related to the more northeasterly gravity trend G4 of Døssing et al. (2013b).
- ii) During the latest Paleocene/earliest Eocene, several large fault zones on Ellesmere Island show sinistral strike-slip motion in a partly transpressive regime, i.e., Eureka Stage 1 of Piepjohn et al. (2016). This indicates that the earliest opening of the Eurasia Basin was partly accommodated by sinistral strike-slip between crustal blocks of the present Ellesmere Island as a result of the North American plate including the Pearya terrane moving relative to Greenland (Fig. 12).
- iii) The initial rifting of the Eurasia Basin included the Yermak Plateau north and west of a small left-lateral offset at 81°N, 17°E northwest of Nordaustlandet (Figs. 2 & 12). Crustal extension of up to 150 km within the Sophia Basin did not focus into a spreading centre (Geissler & Jokat, 2004; Engen et al., 2008) and required dextral slip (de Geer Fault) between Greenland and Spitsbergen close to the coast of Spitsbergen to link with opening of the Norwegian/Greenland Sea. The de Geer Fault may have been active until late early Eocene (Chron 22) to explain the origin of the Sophia Basin (Fig. 12).

The plate boundary between Svalbard and Greenland during the Paleogene was most likely a wide zone of anastomosing faults where the de Geer Fault and subsequently strands of the Hornsund Fault Zone were the significant tectonic lineaments. A narrow continental sliver which included the western part of the Yermak Plateau and Prins Karls Forland moved initially as part of Greenland as the Sophia Basin opened. Shear motion along the de Geer Fault close to the coast and through Forlandsundet ceased by the late Eocene and a tensional regime became dominant (Kleinspehn & Teyssier, 2016). The larger picture of the complexity of contemporary parallel faults between the Mohns and Gakkel spreading centres during the Eocene is manifested to the south by detached slivers of continental crust such as the Hovgard Ridge (Johnson & Eckhoff, 1966; Myhre & Eldholm, 1988; Faleide et al., 2008) and the East Greenland Ridge (Døssing & Funck, 2012). The initial dextral slip off the coast of West Spitsbergen would have been associated with the de Geer Fault, and later the Hornsund Fault Zone became important by the end of early Eocene (Chron 22). On the Greenland side, the Trolle Land Fault System (Fig. 12) was formed in the Carboniferous (Håkansson & Pedersen, 1982; Pedersen & Håkansson, 1999). The Paleocene–Eocene Kilen Event was characterised by N–S directed compression which generated basin inversion, but strike-slip motion was minor (Pedersen & Håkansson, 1999; von Gosen & Piepjohn, 2003; Svennevig et al., 2016).

Modelling studies also advocate an early Cenozoic strike-slip boundary proximal to the basement-involved foreland thrust complexes along the coast of West Spitsbergen (Leever et al., 2011). An analogue model representing two sediment-covered basement plates forced by dextral motion with 15° convergence to produce a doubly vergent wedge; a largely undeformed retro-wedge to the west, and an internally deformed and tapered pro-wedge towards the east. The surface expression of the shear zone which separates the two parts and their respective differences in the degree of basement-involved thrusting, is positioned slightly to the west of the main dextral plate motion. Leever et al. (2011) suggested that the main shear zone may relate to slip close to the present coast – a site which later developed into the coast-parallel graben (Kleinspehn & Teyssier, 2016). Shear at the western boundary of the retro-wedge may represent a zone of weakness co-located with the Hornsund

Fault Zone. The model also suggests deformation affected only the Eurasia plate and did not extend significantly into the interior of the juxtaposed Greenland plate.

The continuation of the de Geer Fault north of Spitsbergen interpreted as the eastern edge of the crustal block which includes Sverdrup Bank is offset to the east with respect to the trend of the coast-parallel graben (Figs. 2, 5 & 8). The NE-trending Danskøya Basin which connects these two trends, is located on top of a crustal-scale detachment plane (Fig. 8, northern crustal transect). We suggest this offset in the de Geer Fault and possibly also the Kap Cannon Thrust (von Gosen & Piepjohn, 1999; Tegner et al., 2011) and motion on the Harder Fiord Fault Zone (von Gosen & Piepjohn, 2003) could be the result of stresses caused by a restraining bend of the Hornsund Fault Zone or associated splays connecting to the west with faults in the Ellesmere domain (Fig. 12). The NE-offset of the de Geer Fault north of Spitsbergen is analogous to observations from the exposed thrust-and-fold belt between the Ymerbukta Fault and Kongsfjorden (Bergh et al., 2000; Piepjohn et al., 2001; Saalman & Thiedig, 2002) where the motion is slightly different from the easterly direction of tectonic transport south of Isfjorden (Dallmann, 2015). Here, the possible explanations for the difference in tectonic transport direction along the fold-and-thrust belt are changes in stresses at a restraining bend of the regional transform fault in the Kongsfjorden area (Steel et al., 1985; Gabrielsen et al., 1992), pinning or buttressing against a fault (Saalman & Thiedig, 2002) or basement north of Kongsfjorden (Dallmann et al., 1993; Lyberis & Manby, 1993) or variable degrees of coupled and decoupled transpressional motion (Maher & Craddock, 1988; Maher et al., 1997; Bergh et al., 2000).

The opening of the Sophia Basin would have followed the direction of opening of the Eurasia Basin as indicated by the thick white arrow in Fig. 2. This creates an overlap when the motion of the present bathymetry of the plateau is backtracked. We consider the circular-shaped, 65 km-wide, northeastern end of Yermak Plateau to be a younger feature of volcanic origin. The emplacement of the feature was probably facilitated by increased volcanic production at the termination of the Gakkel Ridge against the Yermak continental block before the block split and separated the Morris Jesup and Yermak submarine structures.

Conclusions

The Yermak Plateau (500–1500 m w.d.) extends north for about 200 km from the continental shelf north of West Spitsbergen and presents an enigma in plate-tectonic reconstructions because of overlap with a conjugate feature north of Greenland, the Morris Jesup Spur.

We have used a hovercraft platform to access the ice-covered areas north of Svalbard and obtained 21 successful dredge hauls from three known basement outcrops on the Yermak Plateau. The lithologies recovered from two sites on the Sverdrup Bank on the north-trending part of the plateau are predominantly (63–84%) metamorphic rocks accompanied by sedimentary (13–23%) and igneous rocks (3–13%). All 269 rock samples are considered to have equivalents in the geology of northwestern Spitsbergen. Rocks recovered from a site farther northeast on the plateau are mostly sediments (53%), but the largest fragments are alkaline basalt and the abundance of metamorphic rocks is less (20%).

The presence of a continental outlier north of Spitsbergen coupled with the existence of the Sophia Basin between the outlier and the continent imply initial dextral motion inboard of the Hornsund Fault Zone. Further support for a major coast-parallel shear zone comes from the presence of a <20 km-wide zone of lower seismic velocities which extend down to mid-crustal depths. Depressed seismic velocities are a ubiquitous geophysical signature associated with large-offset continental strike-slip faults such as the San Andreas Fault System, the Dead Sea Fault and the North Anatolian Fault.

We envision a kinematic scenario where the Yermak Plateau and a narrow crustal block including Prins Karls Forland moved with Greenland during the initial opening up to about Chron 22 at least. As a result, the Sophia Basin opened by crustal extension and the motion was accommodated by shear along the de Geer Fault close to the west coast of Spitsbergen. The de Geer Fault was subsequently offset to the east north of Spitsbergen and the Danskøya Basin formed in the transfer zone. The offset could have been induced by restraining bends generated by splays of the Hornsund Fault Zone to the west. Volcanism at the eastern end of the Yermak Plateau between Chrons 22 and -18 extended the plateau by about 65 km, and before Chron 13 the Gakkel Ridge propagated into the continental margin of Greenland and isolated the plateau in its present form. The Hornsund Fault Zone was probably initiated in the Paleogene and became the main shear boundary after Chron 13.

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References

- Austegard, A. 1982: Velocity analysis of sonobuoy data from the northern Svalbard margin. *Scientific Report 9*, University of Bergen Seismological Observatory, Bergen, Norway, 13 pp.
- Barnett-Moore, N., Muller, D., Williams, S., Skogseid, J. & Seton, M. 2016: A reconstruction of the North Atlantic since the earliest Jurassic. *Basin Research* 30, 160–185. <https://doi.org/10.1111/bre.12214>.
- Bennett, M.R., Hambrey, M.J. & Huddart, D. 1997: Modification of clast shape in high-arctic glacial environments. *Journal of Sedimentary Research* 67, 550–559. <https://doi.org/10.1306/D42685CC-2B26-11D7-8648000102C1865D>.
- Ben-Zion, Y., & Sammis, C.G. 2003: Characterization of fault zones. *Pure and Applied Geophysics* 160, 677–715. <https://doi.org/10.1007/PL00012554>.
- Ben-Zion, Y., Peng, Z., Lewis, M. & McGuire, J. 2007: High Resolution Imaging of Fault Zone Structures with Seismic Fault Zone Waves. *Scientific Drilling Special Issue 1*, 78–79. <https://doi.org/10.5194/sd-SpecialIssue-78-2007>.
- Bergh, S.G., Braathen, A. & Andresen A. 1997: Interaction of Basement-Involved and Thin-Skinned Tectonism in the Tertiary Fold-Thrust Belt of Central Spitsbergen, Svalbard. *American Association of Petroleum Geologists* 81, 637–661.
- Bergh, S.G., Maher, H.D. & Braathen, A. 2000: Tertiary divergent thrust directions from partitioned transpression, Brøggerhalvøya, Spitsbergen. *Norsk Geologisk Tidsskrift* 80, 63–82. <https://doi.org/10.1080/002919600750042573>.

- Bergh S. G., Grogan P. 2003: Tertiary structure of the Sørkapp-Hornsund Region, South Spitsbergen, and implications for the offshore southern extension of the fold-thrust Belt. *Norwegian Journal of Geology* 83, 43–60.
- Berglar, K., Franke, D., Schreckenberger, B. & Damm, V. 2016: Initial opening of the Eurasia Basin. *Frontiers in Earth Science* 4, article 91.
<https://doi.org/10.3389/feart.2016.00091>.
- Birkenmajer, K. 1972: Tertiary history of Spitsbergen and continental drift. *Acta Polonica* 22, 193–218.
- Blinova, M., Thorsen, R., Mjelde, R. & Faleide, J.I. 2009: Structure and evolution of the Bellsund Graben between Forlandsundet and Bellsund (Spitsbergen) based on marine seismic data. *Norwegian Journal of Geology* 89, 215–228.
- Boulton, G.S. 1978: Boulder shapes and grain-size distributions of debris as indicators of transport paths through a glacier and till genesis. *Sedimentology* 25, 773–799.
<https://doi.org/10.1111/j.1365-3091.1978.tb00329.x>.
- Braathen, A., Osmundsen, P.T., Maher, H., & Ganerød, M. 2017: The Keisarhjelmen detachment records Silurian–Devonian extensional collapse in Northern Svalbard. *Terra Nova* 30, 34–39.
<https://doi.org/10.1111/ter.12305>.
- Breivik, A.J., Verhoef, J. & Faleide, J.-I. 1999: Effect of thermal contrasts on gravity modeling at passive margins: Results from the western Barents Sea. *Journal of Geophysical Research* 104, 15293–15311.
<https://doi.org/10.1029/1998JB900022>.
- Breivik, A.J., Mjelde, R., Grogan, P., Shimamura, H., Murai, Y. & Nishimura, Y. 2003: Crustal structure and transform margin development south of Svalbard based on ocean bottom seismometer data. *Tectonophysics* 369, 37–70. [https://doi.org/10.1016/S0040-1951\(03\)00131-8](https://doi.org/10.1016/S0040-1951(03)00131-8).
- Brozena, J., Childers, V., Lawver, L., Gahagan, L., Forsberg, R., Faleide, J.I. & Eldholm, O. 2003: New aerogeophysical study of the Eurasia Basin and Lomonosov Ridge: Implications for basin development. *Geology* 31, 825–828. <https://doi.org/10.1130/G19528.1>.
- CASE Team 2001: The Evolution of the West Spitsbergen Fold-and-Thrust Belt. In Tessensohn, F. (ed.): *Intra-continental Fold Belts CASEE 1: West Spitsbergen*. Geologisches Jahrbuch 91, 733–773.
- Chernykh, A.A. & Krylov, A.A. 2011: Sedimentogenesis in the Amundsen Basin from Geophysical and Drilling Evidence on Lomonosov Ridge. *Doklady Earth Sciences* 440, 1372–1376.
<https://doi.org/10.1134/S1028334X11100011>.
- Craddock, C., Hauser, E.C., Maher, H., Sun, Y. & Guo-Qiang, Z. 1985. Tectonic evolution of the West Spitsbergen Fold Belt. *Tectonophysics* 114, 193–211. [https://doi.org/10.1016/0040-1951\(85\)90013-7](https://doi.org/10.1016/0040-1951(85)90013-7).
- Crane, K., Eldholm, O., Myhre, A.M. & Sundvor, E. 1982: Thermal implications for the evolution of the Spitsbergen Transform Fault. *Tectonophysics* 89, 1–32. [https://doi.org/10.1016/0040-1951\(82\)90032-4](https://doi.org/10.1016/0040-1951(82)90032-4).
- Crane, K., Sundvor, E., Foucher, J.P., Hobart, M., Myhre, A.M. & LeDouaran, S. 1988: Thermal Evolution of the Western Svalbard Margin, *Marine Geophysical Researches* 9, 165–194.
<https://doi.org/10.1007/BF00369247>.

- Czuba, W., Ritzmann, O., Nishimura, Y., Grad, M., Mjelde, R., Guterech, A. & Jokat, W. 2005: Crustal structure of northern Spitsbergen along the deep seismic between Molloy Deep and Nordaustlandet. *Geophysical Journal International* 161, 347–364. <https://doi.org/10.1111/j.1365-246X.2005.02593.x>.
- Dallmann, W.K. 1992: Multiphase tectonic evolution of the Sørkapp–Hornsund mobile zone (Devonian, Carboniferous, Tertiary), Svalbard. *Norsk Geologisk Tidsskrift* 72, 49–66.
- Dallmann, W.K. 2015: *Geoscience atlas of Svalbard*. Norsk Polarinstitutt Report Series 148, 292 pp.
- Dallmann, W.K., Ohta, Y. & Andresen, A. 1988: Tertiary Tectonics of Svalbard. Extended Abstracts Symposium, Oslo 26–27 April 1988, *Norsk Polarinstitutt Rapport Nr. 46*, 104 pp.
- Dallmann, W., Andresen, A., Bergh, S.G., Maher, H. & Ohta, Y. 1993: Tertiary fold-and-thrust belt of Spitsbergen, Svalbard. *Compilation map, summary and bibliography*. Norwegian Polar Institute Report 128, 46 pp.
- De Geer, G. 1912: Kontinentale Niveauveränderungen im Norden Europas. *Proceedings 11th International Geological Congress*, pp. 849–861.
- De Geer, G. 1919: On the physiographic evolution of Spitzbergen, explaining the present attitude of the coal horizons. *Geografiska Annaler A1*, 161–192. <https://doi.org/10.1080/20014422.1919.11880646>.
- De Geer, G. 1926: Om de geografiske huvudproblemen i nordpolsområdet. *Ymer*, Hefte 2, 133–145.
- DESERT Group 2004: The crustal structure of the Dead Sea Transform. *Geophysical Journal International* 156, 655–681.
- Du Toit, A.L. 1937: *Our wandering continents*. Oliver and Boyd, Edinburgh, 366 pp.
- Døssing A. & Funck, T. 2012: Greenland Fracture Zone– East Greenland Ridge(s) revisited: Indications of a C22-change in plate motion? *Journal of Geophysical Research* 117, B01103, 22 pp. <https://doi.org/10.1029/2011JB008393>.
- Døssing, A., Hopper, J.R., Olesen, A.V., Rasmussen, T.M. & Halpenny, J. 2013b: New aero gravity results from the Arctic: Linking the latest Cretaceous–early Cenozoic plate kinematics of the North Atlantic and Arctic Ocean. *Geochemistry, Geophysics, Geosystems* 14, 4044–4065. <https://doi.org/10.1002/ggge.20253>.
- Døssing, A., Hansen, T.M., Olesen, A.V., Hopper, J.R. & Funck, T. 2014: Gravity inversion predicts the nature of the Amundsen Basin and its continental borderlands near Greenland. *Earth and Planetary Science Letters* 408, 132–145. <https://doi.org/10.1016/j.epsl.2014.10.011>.
- Eiken, O. 1985: Seismic mapping of the post-Caledonian strata in Svalbard. *Polar Research* 3, 167–176. <https://doi.org/10.1111/j.1751-8369.1985.tb00505.x>.
- Eiken, O. 1992: An outline of the northwestern Svalbard continental margin. In Vorren, T., Bergsager, E., Dahl-Stamnes, Ø.A., Holter, E., Johansen, B., Lie, E. & Lund, T.B. (eds.), *Arctic Geology and Petroleum Potential Special Publication 2*, Norwegian Petroleum Society, pp 619–629. <https://doi.org/10.1016/B978-0-444-88943-0.50040-X>.
- Eiken, O. 1994: *Seismic Atlas of Western Svalbard*. Norsk Polarinstitutt Meddelelser 130, 73 pp.

Eiken, O., & Austegard, A. 1987: The Tertiary orogenic belt of West-Spitsbergen: Seismic expressions of the offshore sedimentary basins. *Norsk Geologisk Tidsskrift* 67, 383–394.

Eldholm, O., Faleide, J.-I. & Myhre, A.M. 1987: Continent-ocean transition at the western Barents Sea/Svalbard continental margin. *Geology* 15, 1118–1122.

[https://doi.org/10.1130/0091-7613\(1987\)15<1118:CTATWB>2.0.CO;2](https://doi.org/10.1130/0091-7613(1987)15<1118:CTATWB>2.0.CO;2).

Elverhøi, A. & Grønlie, G. 1981: Diagenetic and Sedimentologic Explanation for High Seismic Velocity and Low Porosity in Mesozoic–Tertiary Sediments, Svalbard Region. *Bulletin American Association Petroleum Geologists* 65, 145–153. <https://doi.org/10.1306/03B599C2-16D1-11D7-8645000102C1865D>.

Engen, Ø., Faleide, J.I. & Karlberg Dyreng, T. 2008: Opening of the Fram Strait gateway: A review of plate tectonic constraints. *Tectonophysics* 450, 51–69. <https://doi.org/10.1016/j.tecto.2008.01.002>.

Evertsen, E.C. 1988: *Analyse av refrakterte innsatser på refleksjonsdata - metodikk og anvendelse*. Cand. Scient. Thesis, Institute of Solid Earth Physics, University of Bergen, 109 pp.

Faleide, J.I., Tsikalas, F., Breivik, A.J., Mjelde, R., Ritzmann, O., Engen, Ø., Wilson, J. & Eldholm, O. 2008: Structure and evolution of the continental margin off Norway and the Barents Sea. *Episodes* 31, 82–91. <https://doi.org/10.18814/epiugs/2008/v31i1/012>.

Faleide, J.-I., Bjørlykke, K. & Gabrielsen, R.H. 2010: Geology of the Norwegian Continental Shelf. In Bjørlykke, K. (ed.): *Petroleum Geoscience: From Sedimentary Environments to Rock Physics*. https://doi.org/10.1007/978-3-642-02332-3_22.

Faulkner, D.R., Lewis, A.C. & Rutter, E.H. 2003: On the internal structure and mechanics of large strike slip fault zones: Field observations of the Carboneras Fault in southeastern Spain. *Tectonophysics* 367, 235–251. [https://doi.org/10.1016/S0040-1951\(03\)00134-3](https://doi.org/10.1016/S0040-1951(03)00134-3).

Feden, R.H., Vogt, P.R. & Fleming, H.S. 1979: Magnetic and bathymetric evidence for the “Yermakhot spot” northwest of Svalbard in the Arctic Ocean. *Earth and Planetary Science Letters* 44, 18–38. [https://doi.org/10.1016/0012-821X\(79\)90004-9](https://doi.org/10.1016/0012-821X(79)90004-9).

Gabrielsen, R., Færseth, R.B., Jensen, L.N., Kalheim, J.E. & Riis, F. 1990: Structural elements of the Norwegian continental shelf. Part II: The Norwegian Sea Region. *Norwegian Petroleum Directorate Bulletin* 6, 33 pp.

Gabrielsen, R.H., Kløvjan, O.S., Haugsbø, H., Midbøe, P., Nøttvedt, A., Rasmussen, E. & Skott, P.H. 1992: A structural outline of Forlandsundet Graben, Prins Karls Forland, Svalbard. *Norsk Geologisk Tidsskrift* 72, 105–120.

Gaina, C., Roest, W.R. & Muller, D. 2002: Late Cretaceous–Cenozoic Deformation of Northeast Asia. *Earth and Planetary Science Letters* 197, 273–286. [https://doi.org/10.1016/S0012-821X\(02\)00499-5](https://doi.org/10.1016/S0012-821X(02)00499-5).

Gaina, C., Gernigon, L. & Ball, P. 2009: Paleocene–Recent plate boundaries in the NE Atlantic and the formation of the Jan Mayen microcontinent. *Journal Geological Society* 166, 601–616. <https://doi.org/10.1144/0016-76492008-112>.

- Gaina, C., Nasuti, A., Kimbell, G. & Blischke, A. 2019: Break-up and seafloor spreading domains in the NE Atlantic. In Péron-Pinvidic, G., Hopper, J.R., Stoker, M.S., Gaina, C., Doornenbal, J.C., Funck, T. & Årting, U.E. (eds): *The NE Atlantic Region: A Reappraisal of Crustal Structure, Tectonostratigraphy and Magmatic Evolution*. Geological Society, London Special Publication 447, 393–417. <https://doi.org/10.1144/SP447.12>.
- Gebhardt, A.C., Jokat, W., Niessen, F., Matthiessen, J., Geissler, W.H. & Schenke, H.W. 2011: Ice sheet grounding and ice berg plow marks on the northern and central Yermak Plateau revealed by geophysical data. *Quaternary Science Review* 30, 1726–1738. <https://doi.org/10.1016/j.quascirev.2011.03.016>.
- Geissler, W.H. & Jokat, W. 2004: A geophysical study of the northern Svalbard continental margin. *Geophysical Journal International* 158, 50–66. <https://doi.org/10.1111/j.1365-246X.2004.02315.x>.
- Geissler, W.H., Jokat, W. & Brekke, H. 2011: The Yermak Plateau in the Arctic Ocean in the light of reflection seismic data – implication for its tectonic and sedimentary evolution. *Geophysical Journal International* 187, 1334–1362. <https://doi.org/10.1111/j.1365-246X.2011.05197.x>.
- Gion, A.M., Williams, S.E. & Muller, R. 2017: A reconstruction of the Eureka Orogeny incorporating deformation constraints. *Tectonics* 36, 304–320. <https://doi.org/10.1002/2015TC004094>.
- Gjengedal, J. 2004: *Ei geofysisk undersøkelse av Nansenbassenget og Yermakplatået*. Cand. Scient. Thesis, Dept. of Earth Science, University of Bergen, 160 pp.
- Glebovsky, V.Y., Kaminsky, V.D., Minakov, A.N., Merky'ev, S.A., Childers, V. & Brozena, J.M. 2006: Formation of the Eurasia Basin in the Arctic Ocean as Inferred from Geohistorical Analysis of the Anomalous Magnetic Field. *Geotectonics* 40, 263–281. <https://doi.org/10.1134/S0016852106040029>.
- Gradstein, F., Ogg, J., Schmitz, M. & Ogg, G. 2012: *The Geologic Time Scale 2012*. Elsevier Publishing Company, 1176 pp.
- Henriksen, N. 2005: *Grønlands geologiske udvikling: fra urtid til nåtid*. Danmarks og Grønlands Geologiske Undersøgelse, København, 270 pp.
- Håkansson, E. & Pedersen, S.A.S 1982. Late Paleozoic to Tertiary evolution on the continental margin of North Greenland. *Canadian Society of Petroleum Geologists Memoir* 8, 331–348.
- Jackson, H.R. & Gunnarsson, K. 1990: Reconstructions of the Arctic: Mesozoic to Present. *Tectonophysics* 172, 303–322. [https://doi.org/10.1016/0040-1951\(90\)90037-9](https://doi.org/10.1016/0040-1951(90)90037-9).
- Jackson, H.R., Johnson, G.L., Sundvor, E. & Myhre, A.M. 1984: The Yermak Plateau: Formed at a Triple Junction. *Journal Geophysical Research* 89, 3223–3232. <https://doi.org/10.1029/JB089iB05p03223>.
- Jakobsson, M., Mayer, L., Coakley, B., Dowdeswell, J.A., Forbes, S., Fridman, B., Hodnesdal, H., Noormets, R., Pedersen, R., Rebecsco, M., Schenke, H.W., Zarayskaya, Y., Accettella, D., Armstrong, A., Anderson, R.M., Bienhoff, P., Camerlenghi, A., Church, I., Edwards, M., Gardner, J.V., Hall, J.K., Hell, B., Hestvik, O., Kristoffersen, Y., Marcussen, C., Mohammad, R., Mosher, D., Nghiem, S.V., Pedrosa, M.T., Travaglini, P.G. & Weatherall, P. 2012: The International Bathymetric Chart of the Arctic Ocean (IBCAO) Version 3.0. *Geophysical Research Letters* 39, L12609. <https://doi.org/10.1029/2012GL052219>.
- Johnson, G.L. & Eckhoff, O.B. 1966: Bathymetry of the North Greenland Sea. *Deep-Sea Research* 13, 1161–1173. [https://doi.org/10.1016/0011-7471\(66\)90707-8](https://doi.org/10.1016/0011-7471(66)90707-8).

- Jones, R.R. & Tanner, P.W. 1995: Strain partitioning in transpression zones. *Journal of Structural Geology* 17, 793–802. [https://doi.org/10.1016/0191-8141\(94\)00102-6](https://doi.org/10.1016/0191-8141(94)00102-6).
- Jokat, W. & Micksch, U. 2004: Sedimentary structure of the Nansen and Amundsen basins, Arctic Ocean. *Geophysical Research Letters* 31, L02603. <https://doi.org/10.1029/2003GL018352>.
- Jokat, W., Weigelt, E., Kristoffersen, Y., Rasmussen, T. & Schöne, T. 1995: Geophysical and Bathymetric Results from Morris Jesup Rise, Yermak Plateau and Gakkel Ridge. *Geophysical Journal International* 123, 601–610. <https://doi.org/10.1111/j.1365-246X.1995.tb06874.x>.
- Jokat, W., Geissler, W.H., & Voss, M. 2008: Basement structure of the north-western Yermak Plateau. *Geophysical Research Letter* 35, L05309. <https://doi.org/10.1029/2007GL032892>.
- Jokat, W., Lehmann, P., Damaske, D. & Bradley Nelson, J. 2016: Magnetic signature of North—East Greenland, the Morris Jesup Rise, the Yermak Plateau, the central Fram Strait: Constraints for the rift/drift history between Greenland and Svalbard since the Eocene. *Tectonophysics* 691, 98–109. <https://doi.org/10.1016/j.tecto.2015.12.002>.
- Kleinspehn, K. & Teyssier, C. 2016: Oblique rifting and the Late Eocene–Oligocene demise of Laurasia with inception of Molloy Ridge: Deformation of Forlandsundet Basin, Svalbard. *Tectonophysics* 693, 363–377. <https://doi.org/10.1016/j.tecto.2016.05.010>.
- Kristoffersen, Y., & Hall, J.K. 2014: Hovercraft as a mobile science platform over sea ice in the Arctic Ocean. *Oceanography* 27, 170–179. <http://dx.doi.org/10.5670/oceanog.2014.33>.
- Kristoffersen, Y. & Talwani, M. 1977: Extinct triple junction south of Greenland and the Tertiary motion of Greenland relative to North America. *Geological Society of America Bulletin* 88, 1037–1049. [https://doi.org/10.1130/0016-7606\(1977\)88<1037:ETJSOG>2.0.CO;2](https://doi.org/10.1130/0016-7606(1977)88<1037:ETJSOG>2.0.CO;2).
- Kristoffersen, Y., Coakley, B., Jokat, W., Edwards, M., Brekke, H. & Gjengedal, J. 2004: Seabed erosion on the Lomonosov Ridge, central Arctic Ocean: A tale of deep draft icebergs in the Eurasia Basin and the influence of Atlantic water inflow on iceberg motion? *Paleoceanography* 19, PA3006. <https://doi.org/10.1029/2003PA000985>.
- Lee, J.-C., Angelier, J., Chu, H.-T., Yu, S.-B. & Hu, J.-C. 1998: Plate-boundary strain partitioning along the sinistral collision suture of the Philippine and Eurasian plates: Analysis of geodetic data and geological observation in southeastern Taiwan. *Tectonics* 17, 859–871. <https://doi.org/10.1029/98TC02205>.
- Leever, K., Gabrielsen, R., Faleide, J.I. & Braathen, A. 2011: A transpressional origin for the West Spitsbergen fold-and-thrust belt: Insight from analog modeling. *Tectonics* 30, TC2014. <https://doi.org/10.1029/2010TC002753>.
- LePichon, X., Sibuet, J.C. & Francheteau, J. 1977: The fit of the continents around the North Atlantic Ocean. *Tectonophysics* 38, 169–209. [https://doi.org/10.1016/0040-1951\(77\)90210-4](https://doi.org/10.1016/0040-1951(77)90210-4).
- Lettis, W.R. & Hanson K.L. 1991: Crustal strain partitioning: Implications for seismic hazard assessment in western California. *Geology* 19, 559–562. [https://doi.org/10.1130/0091-7613\(1991\)019<0559:CSPIFS>2.3.CO;2](https://doi.org/10.1130/0091-7613(1991)019<0559:CSPIFS>2.3.CO;2).
- Ljones, F., Kuwano, A., Mjelde, R., Breivik, A., Shimamura, H., Murai, Y. & Nishimura, Y. 2004: Crustal transect from the North Atlantic Knipovich Ridge to the Svalbard Margin west of Hornsund. *Tectonophysics* 378, 17–41. <https://doi.org/10.1016/j.tecto.2003.10.003>.

Lyberis, N. & Manby G. 1993: The West Spitsbergen Fold belt: the result of Late Cretaceous–Paleocene Greenland-Svalbard Convergence? *Geological Journal* 28, 125–136.
<https://doi.org/10.1002/gj.3350280203>.

Maher, H.D. & Craddock, C. 1988: Decoupling as an alternate model for transpression during the initial opening of the Norwegian-Greenland Sea. *Polar Research* 6, 137–140.
<https://doi.org/10.1111/j.1751-8369.1988.tb00590.x>.

Maher, H.D., Bergh, S., Braathen, A. & Ohta, Y. 1997: Svartfjella, Eidembukta, and Daudmannsodden lineament: Tertiary orogen-parallel motion in the crystalline hinterland of Spitsbergen's fold-thrust belt. *Tectonics* 16, 88–106. <https://doi.org/10.1029/96TC02616>.

McCaffrey, R., Zwick P.C., Bock, Y., Prawirodirdjo, L., Genrich, J.F., Stevens, C.W., Puntodewo, S.S.O. & Subarya, C. 2000: Strain partitioning during oblique plate convergence in northern Sumatra: Geodetic and seismologic constraints and numerical modeling. *Journal of Geophysical Research* 105, 28365–28376.
<https://doi.org/10.1029/1999JB900362>.

Minakov, A., Faleide, J.I., Glebovsky, V.Y. & Mjelde, R. 2012: Structure and evolution of the northern Barents–Kara Sea continental margin from integrated analysis of potential fields, bathymetry and sparse seismic data. *Geophysical Journal International* 188, 79–102.
<https://doi.org/10.1111/j.1365-246X.2011.05258.x>.

Mooney, W.D., Berzosa, G.C. & Kind, R. 2007: Fault Zones from Top to Bottom: A Geophysical Perspective. In Handy, M.R., Hirth, G. & Hovius, N. (eds.): *Tectonic Faults Agents of Change of a Dynamic Earth*, MIT Press, chapter 2, pp. 9–46.

Morris, A. 1989: Distributed, right-lateral strike-slip in Prins Karls Forland, western Svalbard. *Polar Research* 7, 79–82. <https://doi.org/10.3402/polar.v7i1.6832>.

Murphy, J., Fuis, G., Ryberg, T., Lutter, W., Catchings, R. & Goldman, M. 2010: Detailed P- and S-Wave Velocity Models along the LARSE II Transect, Southern California. *Bulletin Seismological Society of America* 100, 3194–3212. <https://doi.org/10.1785/0120090004>.

Myhre, A. & Eldholm, O. 1988: The Western Svalbard margin (74–80 N). *Marine and Petroleum Geology* 5, 134–156. [https://doi.org/10.1016/0264-8172\(88\)90019-0](https://doi.org/10.1016/0264-8172(88)90019-0).

Myhre, A., Eldholm, O. & Sundvor, E. 1982: The margin between Senja and Spitsbergen fracture zones: Implications from plate tectonics. *Tectonophysics* 89, 33–50.
[https://doi.org/10.1016/0040-1951\(82\)90033-6](https://doi.org/10.1016/0040-1951(82)90033-6).

Nøttvedt, A., Livbjerg, F. & Midbøe, P. 1988: Tertiary deformation of Svalbard –various models and recent advances. *Norsk Polarinstitutt Rapport* 46, 79–84.

Ohta, Y., Krasil'shchikov, A.A., Lepvrier, C. & Teben'kov, A.M. 1995: Northern continuation of Caledonian high-pressure metamorphic rocks in central-western Spitsbergen. *Polar Research* 14, 303–315.
<https://doi.org/10.3402/polar.v14i3.6670>.

Okay, N. & Crane, K. 1993: Thermal Rejuvenation of the Yermak Plateau. *Marine Geophysical Researches* 15, 243–263. <https://doi.org/10.1007/BF01982384>.

Opsahl, J. 1997: *Den sen-kenozoiske sedimentasjonshistoren nordvest for Spitsbergen*. Cand. Scient. Thesis, Univ. of Tromsø, 96 pp.

- Pedersen, S.A.S. & Håkansson, E. 1999. Kronprins Christian Land Orogeny: Deformational Styles of the End Cretaceous Transpressional Mobile Belt in Eastern North Greenland. *Polarforschung* 69, 117–130.
- Petterson, C.H., Tebenkov, A.M., Larionov, A.N., Andresen, A. & Pease, V. 2009. Timing of migmatization and granite genesis in the Northwestern Terrane of Svalbard, Norway: implications for regional correlations in the Arctic Caledonides. *Journal Geological Society* 166, 147–158.
<https://doi.org/10.1144/0016-76492008-023>.
- Piepjoh, K., Theidig, F. & Manby, G. 2001: Nappe stacking on Brøggerhalvøya, NW Spitsbergen. In Tessensohn, F. (ed.) *Intra-Continental Fold Belts – CASE I: West Spitsbergen*. Polar Issue No.7, Geologisches Jahrbuch B91, pp. 55–79.
- Piepjoh, K., von Gosen, W. & Tessensohn, F. 2016: The Eureka deformation in the Arctic: an outline. *Journal Geological Society London* 173, 1007–1024. <https://doi.org/10.1144/jgs2016-081>.
- Rehman, A.U. 2012: *Structural Analysis of the Knølegga Fault Complex, NW Barents Sea*. Master Thesis, Univ. of Oslo, 97 pp.
- Riefstahl, F., Estrada, S., Geissler, W.H., Jokat, W., Stein, R., Kampf, H., Dulski, P., Naumann, R. & Spiegel, C. 2013: Provenance and characteristics of rocks from the Yermak Plateau, Arctic Ocean: Petrographic, geochemical and geochronological constraints. *Marine Geology* 343, 125–145.
<https://doi.org/10.1016/j.margeo.2013.06.009>.
- Ritzmann, O. & Jokat, W. 2003: Crustal structure of northwestern Svalbard and the adjacent Yermak Plateau: evidence for Oligocene detachment tectonics and non-volcanic breakup. *Geophysical Journal International* 152, 139–159. <https://doi.org/10.1046/j.1365-246X.2003.01836.x>.
- Ritzmann, O., Jokat, W., Mjelde, R. & Shimamura, H. 2002: Crustal structure between the Knipovich Ridge and the Van Mijenfjorden (Svalbard). *Marine Geophysical Researches* 23, 379–401.
<https://doi.org/10.1023/B:MARI.0000018168.89762.a4>.
- Ritzmann, O., Jokat, W., Czuba, W., Guterech, A., Mjelde, R. & Nishimura, Y. 2004: A deep seismic transect from Hovgard Ridge to northwestern Svalbard across the continental-ocean transition: a sheared margin study. *Geophysical Journal International* 157, 683–702.
<https://doi.org/10.1111/j.1365-246X.2004.02204.x>.
- Roest, W.R. & Srivastava, S.P. 1989: Sea-floor spreading in the Labrador Sea: A new reconstruction. *Geology* 17, 1000–1003. [https://doi.org/10.1130/0091-7613\(1989\)017<1000:SFSITL>2.3.CO;2](https://doi.org/10.1130/0091-7613(1989)017<1000:SFSITL>2.3.CO;2).
- Saalmann, K. & Thiedig, F. 2002: Thrust tectonics on Brøggerhalvøya and their relationship to the Tertiary West–Spitsbergen Fold-and-Thrust Belt. *Geological Magazine* 139, 47–72.
<https://doi.org/10.1017/S0016756801006069>.
- Schluter, H-U. & Hinz, K. 1978: The Continental Margin of West–Spitzbergen. *Polarforschung* 48, 151–169.
- Shuanggen, J. 2013: GNSS Observations of Crustal Deformation: A Case Study in East Asia, *Geodetic Sciences - Observations, Modeling and Applications*, Chapter 8 Intech Open Publishing, 267–284.
<https://doi.org/10.5772/51536>.

Ritzmann, O., Jokat, W., Czuba, W., Guterech, A., Mjelde, R. & Nishimura, Y. 2004: A deep seismic transect from Hovgard Ridge to northwestern Svalbard across the continental-ocean transition: a sheared margin study. *Geophysical Journal International* 157, 683–702.

<https://doi.org/10.1111/j.1365-246X.2004.02204.x>.

Roest, W.R. & Srivastava, S.P. 1989: Sea-floor spreading in the Labrador Sea: A new reconstruction. *Geology* 17, 1000–1003. [https://doi.org/10.1130/0091-7613\(1989\)017<1000:SFSITL>2.3.CO;2](https://doi.org/10.1130/0091-7613(1989)017<1000:SFSITL>2.3.CO;2).

Saalmann, K. & Thiedig, F. 2002: Thrust tectonics on Brøggerhalvøya and their relationship to the Tertiary West–Spitsbergen Fold-and-Thrust Belt. *Geological Magazine* 139, 47–72.

<https://doi.org/10.1017/S0016756801006069>.

Schluter, H-U. & Hinz, K. 1978: The Continental Margin of West–Spitzbergen. *Polarforschung* 48, 151–169.

Shuanggen, J. 2013: GNSS Observations of Crustal Deformation: A Case Study in East Asia, Geodetic Sciences - Observations, Modeling and Applications, Chapter 8 *Intech Open Publishing*, 267–284.

<https://doi.org/10.5772/51536>.

Sibson, R.H. 2003: Thickness of the seismic slip zone. *Bulletin Seismological Society of America* 93, 1169–1178. <https://doi.org/10.1785/0120020061>.

Srivastava, S.P. & Tapscott, C.R. 1986: Plate kinematics of the North Atlantic. In Vogt, P.R & Tucholke, B.E. (Eds.), *The Western North Atlantic Region. The Geology of North America Volume M*, Geological Society of America, pp. 379–405. <https://doi.org/10.1130/DNAG-GNA-M.379>.

Steel, R., Gjelberg, J., Helland-Hansen, W., Kleinsphen, K., Nøttvedt, A. & Rye-Larsen, M. 1985: The Tertiary strike-slip basins and orogenic belt of Spitsbergen. In Biddle, K.T. & Christie-Blick, N. (eds.): *Strike-Slip Deformation, Basin Formation and Sedimentation*. Society of Economic Paleontologists and Mineralogists Special Publication 37, 339–359. <https://doi.org/10.2110/pec.85.37.0339>.

Sundvor, E. & Austegard, A. 1990: The evolution of the Svalbard margins: Synthesis and new results. In: Bleil, U. & Thiede, J. (eds.): *Geological History of the Polar Oceans: Arctic versus Antarctic*, NATO ASI Series, Kluwer Academic Publisher, pp. 77–94. https://doi.org/10.1007/978-94-009-2029-3_5.

Sundvor, E., & Eldholm, O. 1976: Marine geophysical survey on the continental margin from Bear Island to Hornsund, Spitsbergen. *Seismological Observatory, Scientific Report No.3*, 29 pp.

Sundvor, E., Sellevoll, M., Gidskehaug, A. & Eldholm, O. 1978: Seismic Investigation on the Western and Northern Margin off Svalbard. *Polarforschung* 48, 41–43.

Svennevig, K. Guarnieri, P. & Stemmerik, L. 2016: Tectonic inversion in the Wandel Sea Basin: A new structural model of Kilen (eastern North Greenland). *Tectonics* 35, 2896–2917, <https://doi.org/10.1002/2016TC004152>.

Tegner, C., Storey, M., Holm, P.M., Thorarinsson, S.B., Zhao, X., Lo, C.-H. & Knudsen, M.F. 2011: Magmatism and Eureka deformation in the High Arctic Large Igneous Province: 40Ar–39Ar age of Kap Washington Group volcanics, North Greenland. *Earth & Planetary Science Letters* 303, 203–214.

<https://doi.org/10.1016/j.epsl.2010.12.047>.

- ten Brink, U.S., Al-Zoubi, A.S., Flores, C.H., Rotstein, Y., Qabbani, I., Harder, S.H. & Keller, G.R. 2006: Seismic imaging of deep low-velocity zone beneath the Dead Sea basin and transform fault: Implications of strain localization and crustal rigidity. *Geophysical Research Letter* 33, L24314. <https://doi.org/10.1029/2006GL027890>.
- Vogt, P.R., Taylor, P., Kovacs, L.C., & Johnson, G.L. 1979: Detailed aeromagnetic investigation of the Arctic Basin. *Journal of Geophysical Research* 84, 1071–1089. <https://doi.org/10.1029/JB084iB03p01071>.
- von Gosen, W. & Piepjohn, K. 1999: Evolution of the Kap Cannon Thrust Zone (north Greenland). *Tectonics* 18, 1004–1026. <https://doi.org/10.1029/1999TC900035>.
- von Gosen, W & Piepjohn, K. 2001: Thrust tectonics north of Van Keulenfjorden. In Tessensohn, F. (ed.): *Intra-Continental Fold Belts – CASE I: West Spitsbergen*. Polar Issue No.7, Geologisches Jahrbuch B91, 247–272.
- von Gosen, W & Piepjohn, K. 2003: Eureka transpressive deformation in the Wandel Hav Mobile Belt (northeast Greenland). *Tectonics* 22, 1039. <https://doi.org/10.1029/2001TC901040>.
- Wallace, R.E. 1991: *The San Andreas Fault System*. Professional paper 1515, United States Geological Survey. <https://doi.org/10.3133/pp1515>.
- Wdowinski, S., Sudman, Y. & Bock, Y. 2001: Geodetic detection of active faults in S. California. *Geophysical Research Letters* 28, 2321–2324. <https://doi.org/10.1029/2000GL012637>.
- Wegener, A. 1912: Die Entstehung der Kontinente. *Geologische Rundschau* 3, 276–292. <https://doi.org/10.1007/BF02202896>.
- Wegmann, C.E. (1948): Geological tests of the hypothesis of continental drift in the Arctic regions. *Meddelelser om Grønland* 144, 48 pp.
- Welbon, A.I. & Maher Jr., H.D. 1992: Tertiary tectonism and basin inversion of the St. Jonsfjorden region, Svalbard. *Journal of Structural Geology* 14, 41–55. [https://doi.org/10.1016/0191-8141\(92\)90143-K](https://doi.org/10.1016/0191-8141(92)90143-K).
- Wessel, P., Smith, W., Scharroo, R., Luis, J. & Wobbe, F. 2013: GMT 5: A major new release of the Generic Mapping Tools: Improved version released. *Eos, Transactions of the American Geophysical Union* 94, 409–410
- Wilson, J.T. 1965: A new class of faults and their bearing on continental drift. *Nature* 207, 343–347. <https://doi.org/10.1038/207343a0>.