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Key Points:

- Syn-sedimentary Triassic normal faulting in eastern Svalbard suggests the maximum horizontal stress was oriented NW-SE to WNW-ESE
- A Cretaceous regional jointing episode occurred in Svalbard with the maximum horizontal stress oriented approximately E-W
- Svalbard stresses changed as plate activity shifted from the Urals (to E) to the Amerasian Basin (to N) to the Atlantic transform (to W)

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Mesozoic-Cenozoic Regional Stress Field Evolution in Svalbard

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Abstract Cooling fracture orientations in diabase sills associated with the Cretaceous High Arctic Large Igneous Province and syn-sedimentary Triassic faults help constrain a model for Svalbard's (NE Barents Shelf) Mesozoic stress field evolution. Fracture data from Edgeøya and adjacent islands in SE Svalbard, from S Spitsbergen, and from literature were used to model preferred orientations and temporal relationships. Orthogonal, roughly E-W and N-S, joints and veins in sills from SE Svalbard are interpreted as cooling fractures influenced by the ambient stress field. Aligned preferred orientations within the Triassic host strata are associated with a regional Cretaceous jointing episode driven by sill emplacement and/or erosional unloading. The regional maximum horizontal stress (likely σ_1) is inferred to have been parallel to a dominant $\approx$ E-W set. Spitsbergen's more complex joint patterns are associated with proximity to the Cenozoic West Spitsbergen Fold-and-Thrust Belt, but $\approx$ E-W and $\approx$ N-S orientations occur and are typically the earlier set. Syn-sedimentary, $\approx$ NW-SE striking, Triassic normal faults in SE Svalbard aligned with the maximum horizontal stress indicate a Triassic to Cretaceous counterclockwise stress field shift, with additional counterclockwise shifting during Cenozoic dextral transpression between Svalbard and Greenland. Localized joint preferred orientations consistent with both decoupled and coupled transpression occur. Changes in the regional maximum horizontal stress and deformation regime may reflect timing of which plate margin was crucial in influencing Svalbard's plate interior stress field, starting with Triassic Uralian activity to the E, then Cretaceous Amerasian Basin development to the NW, culminating with Cenozoic dextral transpression and transtension to the SW.

1. Introduction

Regional intraplate stress and strain fields have been documented and attributed in significant part to plate margin boundary forces (e.g., Coblenz & Richardson, 1995; Sandiford, 2010). Regional joint sets are one manifestation of such fields (e.g., Engelder, 1985; Engelder & Whitaker, 2006; Hancock & Engelder, 1989) and provide the potential to track paleo-stress fields and better understand tectonic histories (e.g., Herman, 2005). However, because of a multiplicity of loading paths and reactivation, the difficulty of constraining the timing of joint formation is challenging (Gale et al., 2014). Intraplate faulting can also be attributed to internal stress fields (e.g., Towend & Zoback, 2000).

On the Arctic Archipelago of Svalbard (Figure 1) two opportunities exist to constrain the timing of fracture generation within the Barents Shelf during the Mesozoic. During the Cretaceous Svalbard was marginal to the High Arctic Large Igneous Province (HALIP; e.g., Maher, 2001; Senger, Tveranger, et al., 2014) and a series of diabase sills were emplaced within the platform cover sequence. Associated extrusive rocks exist in Kong Karls Land, the eastern most part of Svalbard (Bailey & Rasmussen, 1997; Olaussen et al., 2019; Senger, Tveranger, et al., 2014; Smith et al., 1976). Cooling joints in plutons are to be expected (Bergbauer & Martel, 1999; Martel & Bergbauer, 1997) and can be influenced by the regional stress field (Bankwitz et al., 2004). Intrusion geometry influences associated cooling joint patterns (Bergbauer et al., 1998) and cooling joints in horizontal sills may be optimal for reflecting the ambient regional stress field due to the simple tabular sill geometry. Tetragonal volume-change related opening mode fractures that reflect regional

Figure 1. Schematic map of localities and tectonic features discussed. Dashed lines enclose the Svalbard archipelago. Red outline—approximate pre-Cenozoic position of Spitsbergen. Relief base map from Jakobsson et al. (2012). WSFTB = West Spitsbergen Fold-and-Thrust Belt.

stresses are known from other geologic settings (e.g., coal cleats, Laubach et al., 2006; Engelder & Whitaker, 2006). Since joints in the sill and host rock are crucial to this effort, they are explored first. A second opportunity is presented by distributed syn-sedimentary normal faulting found on Edgeøya and Hopen that developed during the Carnian and Norian (Figure 1) in eastern Svalbard (Anell et al., 2013; Ogata et al., 2018; Osmundsen et al., 2014). Literature on Cenozoic fracture development and associated stress field history then helps constrain the younger history.

This effort presents: (a) new data on the preferred orientations of opening mode fractures in Early Cretaceous sills and host Triassic strata from study sites on southern Edgeøya (Figure 2), where the tectonic setting is simpler, (b) equivalent new data from southern Spitsbergen (Hornsund area) strata, where the tectonic setting is more complex due to Cenozoic deformation, (c) a summary of the literature on fracture preferred orientations in Triassic strata and diabbases of central Spitsbergen (Lord, 2013; Ogata et al., 2012 and 2014), (d) a description of the kinematics of syn-sedimentary Triassic faults in the Edgeøya (Osmundsen et al., 2014) and Hopen (Lord et al., 2019) areas, and (f) a working model based on this data for the Mesozoic-Cenozoic stress field evolution for Svalbard.

2. Geologic Background

Svalbard has a particularly rich geologic history that many have contributed to elucidating with a considerable body of previous work. Thus, the following summary is necessarily incomplete, focusing on elements gauged to be more relevant to this effort, and on more recent work. The reader is also referred to the Norwegian Polar Institute's map site <https://svalbardkartet.npolar.no/Html5Svb/index.html?viewer=Svalbardkartet>, which includes comprehensive geologic maps, and to a stratigraphic lexicon based on Dallmann (1999) that can be found at https://timescalefoundation.org/resources/NW_Europe_Lex/litho/svalbard/index.htm.

Svalbard's older crystalline rocks include (a) Grenvillian basement, (b) Neoproterozoic to Cambrian metasedimentary rocks that have undergone polyphase Ordovician to Silurian Caledonian deformation and metamorphism that locally includes migmatization and eclogite emplacement (Johansson et al., 2005; Labrousse et al., 2008), (c) syn- and post tectonic Late Silurian to Early Devonian granites and a metamorphic core complex (e.g., Tebenkov et al., 2002, NE Svalbard; Braathen, Osmundsen, et al., 2017, NW Svalbard). A thick Late Silurian through Devonian basin sequence that is exposed in northern Spitsbergen experienced polyphase deformation (e.g., the Ellesmerian/Svalbardian), arguably involving significant sinistral plate motion (McCann, 2000; Pettersson et al., 2010; Piepjohn, 2000). An N-S structural grain as defined by prevailing

Figure 2. Geologic map of eastern Svalbard study sites discussed. (a) S Edgeøya diabase study sites: A = Andretangen; I1 and I2 = Interior Study Sites 1 and 2; P = Pongtongen; S = Svartangen. S Edgeøya Triassic strata study sites: WS = West Skrinhovden; E = Eilefdalen site; SP = Schwarzpynten. Steep normal fault sites discussed: ES = East Skrinhovden; WSP = western Schwarzpynten. Thin-skinned normal fault sites discussed: K = Kvalpynten; T = Tjuvfjordskarvet. (b) Sites discussed between Barentsøya and Olav V Land in eastern Spitsbergen. Maps modified from Norsk Polarinstitut digital geologic map of Svalbard. White interior areas are glaciers. See Table 1 for more details on the stratigraphy.

fault, fold, and foliation trends was subject to subsequent reactivation as illustrated by the tectonic history of the Billefjorden Fault Zone (Haremo et al., 1990; McCann & Dallmann, 1996). Mid-Carboniferous reactivation of the Billefjorden Fault Zone, which had a previous history of strike-slip and reverse motions, produced a rift basin (Bælum & Braathen, 2012; Smyrak-Sikora et al., 2018), which subsequently underwent mild Cenozoic inversion. Carboniferous rift basins underlying younger Mesozoic strata across much of the submerged portion of western Barents Shelf, including the area east of Edgeøya (Anell et al., 2013; Faleide et al., 2008), are prone to Cenozoic reactivation (Kairanov et al., 2018).

Stable platform sedimentation in the Svalbard area occurred from the Late Carboniferous and into the Early Cretaceous. During the Triassic in specific a large deltaic system (Kapp Toscana Group, Table 1) migrated across the Uralian foredeep basin and into the western Barents Shelf (Lundschien et al., 2014; Riis et al., 2008), reaching eastern Svalbard in the Carnian. In addition to this northwest prograding deltaic system, Worsely (2008) suggests an additional Late Triassic sediment source to the north of Svalbard. During Carnian deposition of the Tschermakfjellet and De Geerdalen formations (Table 1), both thick and thin-skinned normal faulting occurred in eastern Svalbard (Osmundsen et al., 2014; Braathen, Midtkandal, et al., 2017, Figure 1). Late Jurassic transgression yielded a thick sequence of organic rich shales across the region (Anell et al., 2014; Dypvik et al., 2002; Koevoets et al., 2018). Sedimentation in the Helvetiafjellet and Carolinefjellet formations (Grundvåg et al., 2019, Table 1) was influenced during the

Table 1
Summary Stratigraphic Table Emphasizing Units Discussed in the Paper

Age	≈Ma	Group	Mentioned Fms (younger to older)	Dominant lithologies	Thickness (m)	Associated events
Cenozoic	66–40	Van Mijenfjorden		Terrestrial, some marine clastics, coal	0–3,000	WSFTB, foreland basin development
Late Cretaceous	100–66	Major hiatus				Regional uplift to N, Amerasian Basin development
Middle Jurassic–Early Cretaceous	170–100	Adventdalen	Carolinefjellet, Helvetiafjellet	Marine mixed clastics/terrestrial clastics/marine shales. HALIP intrusive/extrusive suite	550–1,700+	Initial major transgression, HALIP and regression, then transgression
Late Triassic–Middle Jurassic	235–170	Kapp Toscana	Flatsdalen, De Geerdalen, Tschermakfjellet (Barentsøya and Edgeøya)	Deltaic clastics	70–510+	Deltaic progradation from Uralian source, minor intraplate tectonism
Early Triassic–Middle Triassic	252–235	Sassendalen	Botneheia (Barentsøya and Edgeøya)	Mostly marine clastics	60–870	Stable platform
Permian	270–252	Tempelfjorden	Kapp Starostin	Limestones and cherts	0–460	Stable platform
Late Carboniferous–Early Permian	275–325	Gipshuken	Treskelodden, Hyrnefjellet (for S Spitsbergen)	Terrestrial rift clastics and carbonates, then platform carbonates	0–1,800	Mid-Carboniferous distributed Barents Shelf rifting
Mostly Early Carboniferous	368–330	Billefjorden		Mostly terrestrial quartz arenites, coal	0–1,250	Basal angular unconformity, widespread deposition
Devonian	415–370	Brief hiatus Andre Land		Mainly 'red beds'	0–8,000	Ellesmerian/Svalbardian deformation
	Pre-Devonian basement		Basement metamorphics, intrusives		Grenvillian and Caledonian orogenesis	

Note. Units from Dallmann (1999) and thicknesses from Worsley et al. (1986).

Early Cretaceous by the development of the HALIP and the formation of the Amerasian Basin to the N (e.g., Maher, 2001; Senger, Tveranger, et al., 2014) with attendant development of a northern source terrain (Dypvik et al., 2002; Kairanov et al., 2018; Maher et al., 2004). Corfu et al. (2013) used U-Pb geochronology to constrain the peak of HALIP magmatism on Svalbard and Franz Josef Land (Figure 1) to between 122 and 124 Ma.

Subsequent Cenozoic development of the Eurasian Basin was linked to seafloor spreading in the North Atlantic. This led to a phase of dextral transpression along a linking continental transform system (Hornsund Fault Complex) as Svalbard separated from Greenland (Faleide et al., 2008; Harland, 1969; Piepjohn et al., 2016), producing the West Spitsbergen Fold-and-Thrust Belt (WSFTB) and an associated foreland basin (Helland-Hansen, 1990). The ≈ 300 km long, NNW-SSE trending WSFTB consists of a basement-involved antiformal stack to the W, and a more thin-skinned, E portion and a detachment that extended underneath the foreland basin (Braathen et al., 1999). The associated kinematics evolved significantly, and transpression was at times decoupled with an orogen-perpendicular shortening direction at $\approx 60^\circ$ (Bergh & Grogan, 2003; Braathen & Bergh, 1995; Lepvrier, 1990; Maher & Craddock, 1988). In the Early Oligocene poles of rotation changed and transtension developed as Greenland and the Barents Shelf separated and seafloor spreading initiated (e.g., Faleide et al., 2008; Kleinsphen et al., 1989).

3. Methodology

The term “fracture” is used herein to describe all brittle discontinuities (shear and tensile) and the term opening mode fractures to refer to joints and veins (Pollard & Aydin, 1988). The focus of this study was on determination of fracture set preferred orientations (strike averages), associated dispersion, and proportional contribution of a set to an overall fracture pattern. A basic interpretative assumption used is that preferred orientations of fractures reflect principal stress directions at the time of formation. The following conventions are used: σ_{mh} = maximum horizontal stress, $\sigma_1/\sigma_2/\sigma_3$ = are principal stress, and compressive stresses are positive.

The following fracture orientation data types are utilized: length-weighted strike-trace data from oriented and scaled imagery (both ground based and air photo), traverse data (often from sub-vertical outcrops, some garnered from the literature), and opportunistic (determined by field access and available time in this remote area) data. Supporting information containing the data with descriptive details is provided (see Acknowledgments for details).

A consideration is that the joint pattern in lava flows can vary with vertical position (Aydin & DeGraff, 1988) and, ostensibly, also in sills. For ground-based imagery (from southern Edgeøya), a coarser grain size ($\approx 2\text{--}3$ mm) indicates the sub-horizontal outcrop surfaces were within the sill interior, and not at fine-grained sill margins. The erosional processes that produced such outcrops (glacial, then shoreline related) likely preferentially removed the more highly fractured upper sill margin material. In addition, vertical continuity through the sill of individual joints seen at many sites indicates the joint pattern recorded in the images represents that of the sill interior. However, for the air photo imagery the grain size is unknown and a variable vertical position within the sill may contribute to variance in the fracture pattern seen.

Study sites (Table 2) were selected opportunistically, but with geographic distribution in mind. In many of the study sites, sub-vertical or bedding-perpendicular opening mode fractures were predominant. Bedding was typically sub-horizontal. Where traces of joints were evident on sub-horizontal and/or bedding-parallel outcrop faces, oriented and scaled field images were taken for later analysis (areal sampling of Watkins et al., 2015). With such a perspective, sub-vertical fracture relationships and their relative proportions are more consistently represented.

Care was taken to have the image view axis vertical, and/or bedding perpendicular if the layers were tilted. Within 0.9 to 1.5 m diameter scaled circles, fracture traces were segmented into approximately 10 cm long sections by placing 10 cm diameter circles with their centers on the fractures so that adjacent circles were touching, but not overlapping (e.g., Figures 3c and 3d). Such circles were used as a simple device for dividing the fracture trace into even length segments. Line segments were then drawn within the smaller circles over the fracture traces and their image coordinates used to compute strike orientation. Copies of images with and without circles and segmented traces and image coordinates are available in the supporting

Table 2
Summary Table of Sites, Joint Preferred Orientations, and Ancillary Information

Site	Lat.	Long.	Geologic unit(s)	Data description	P.O. (strike/ proportion)	P.O. (strike/ proportion)	P.O. (strike/ proportion)	P.O. (strike/ proportion)	Comments
Andretangen, Edgeøya	77.43°	22.63°	Diabase	7 photos, 90 fractures, 334 segments	50°/17%	85°/18%	145°/12%	176°/29%	24% modeled at uniform, traverse data dominated by more N-S set
Svarttangen, Edgeøya	77.52°	20.84°	Diabase	7 photos, 118 fractures, 392 segments	22°/20%	85°/37%	147°/11%	174°/32%	0% modeled as uniform
Pongtongen, Edgeøya	77.38°	22.57°	Diabase	6 photos, 102 fractures, 355 segments	18°/24%	93°/44%	145°/7%	174°/14%	Photos closer together, smaller area; 11% modeled as uniform
Interior Site 1, Edgeøya	77.53°	20.87°	Diabase	5 photos, 49 fractures, 214 line segments	25°/46%	83°/14%	123°/21%	166°/7%	12% modeled as uniform
Interior Site 2, Edgeøya	77.52°	20.89°	Diabase	6 photos, 69 fractures, 308 line segments	27°/48%	67°/6%	92°/28%	168°/8%	10% modeled as uniform
Total S Edgeøya diabase	See above	See above	Diabase	31 photos, 432 fractures, 1268 line segments	23°/28%	89°/29%	139°/4%	169°/15%	24% modeled as uniform
NW coast of Kukenhalvøya	78.65°	21.18°	Diabase	≈0.2 km ² area, 230 line segments ≈20 m long	15°/24%	63°/4%	94°/59%	178°/6%	From Norsk Polarinstitutt imagery, bias of topo expression of fractures
Aleeksoya	78.63°	21.29°	Diabase	≈0.6 km ² , 417 line segments ≈25 m long	47°/24%	89°/17%	121°/12%	175°/25%	From Norsk Polarinstitutt imagery, bias of topo expression of fractures
Kapp Muhry	78.67°	21.35°	Diabase	0.07 ≈ km ² , 400 line segments ≈25 m long	1°/22%	28°/17%	89°/19%	111°/35%	From Norsk Polarinstitutt imagery, bias of topo expression of fractures
Southern Edgeøya	77.53° 77.45°	21.57° 20.95°	Tshermakfjellet shales (Tr)	2 sites, 7 photos, 91 fractures, 286 line segments	53°/20%	87°/58%	105°/2%	178°/18%	2% modeled as uniform
Hopen	76°	25°	Triassic strata	195 fractures	17°	64°	145°	177°	Data from Lord (2013), multiple traverses and sites
Treskelodden, S Spitsbergen	76.99°	16.22°	Permian Kapp Starostin Fm.	3 photos, 63 fractures, 274 line segments	5°/35%	55°/20%	88°/25%	150°/17%	3% modeled as uniform
Treskelodden, S Spitsbergen	77.00°	16.20°	Carboniferous Treskelodden Fm.	5 photos, 144 fractures, 262 line segments	20°/2%	49°/36%	84°/14%	153°/34%	14% modeled as uniform
Lidfjellet, S Spitsbergen	76.86°	15.89°	Basal Triassic strata	7 photos, 141 fractures, 404 line segments	29°/10%	53°/37%	119°/31%	172°/7%	7% modeled as uniform
Rafenodden, S Spitsbergen	76.84°	15.68°	Carboniferous Billefjorden Grp.	6 photos, 211 fractures, 549 line segments	11°/41%	91°/49%	139°/2%	162°/8%	0% modeled as uniform
Central Spitsbergen	Various	Various	Triassic strata	$n = 358$	68°	90°	154°	178°	Data from Lord (2013), multiple traverses and sites

Note. Preferred orientations given in clockwise order from North. Where the preferred orientation is from strike length-weighted data it is followed by the model % contribution to the overall distribution. Colored cells are those interpreted as the ≈E-W (blue) and ≈N-S (purple) preferred orientations of a regional orthogonal joint pair.

Figure 3. (a) Length-weighted sliding sector plots of strike distribution of joints for diabase sill sites. Radial axes are the number of 10 cm joint trace segments in 20° sector. Labeled by site name, with number of individual fractures/number of total line segments below. In this and subsequent plots, red is observed while blue is model plot. Additional info in Table 1 and Figure 2 for site locations. (b) Composite sliding sector plot of length-weighted strike distribution from all five sites along with model (parameters in lower right table, P1–P4 are modeled preferred orientations in no particular order). (c, d) Examples of interpreted fracture trace image for images from Andretangen and Svartangen. Smaller circles are used to divide traces into approximately 10 cm long segments. Interpreted and uninterpreted images included in the supplemental documents. Silva and Brunton compasses for scale aligned with N.

information. Variation in the plotted data reflects that both along and between individual fractures. Both line segment and individual joint counts are provided (Table 2 and Figure 3).

Circle and line segment placement was done manually, allowing exclusion of weathering-related fractures (shorter, more irregular, cutting corners of larger fracture blocks, and spall shaped with shallow dips). The strike angle for each line segment was plotted, resulting in a length-weighted representation of fracture trace strikes (primary data, including images of the interpreted fracture traces are available in the supporting

information). Segments that were truncated or truncating another fracture were also distinguished. More sophisticated analysis of fracture pattern attributes (e.g., as described in Watkins et al., 2015) was considered unwarranted for the purpose of this study given a simpler goal of establishing fracture preferred orientations and their relative timing.

Advantage was also taken of imagery available from the Norwegian Polar Institute's online map TopoSvalbard (<http://toposvalbard.npolar.no/>) that includes coverage of extensive diabase sill outcrop exposures just N of Barentsøya (Figure 2b), where fracture traces are readily evident. Resolution varied, but fractures several meters apart could typically be clearly delineated. Tracing every fracture evident in these images was time prohibitive. Traces drawn were based on fracture clarity in the image and spaced so as to provide roughly even trace coverage where the outcrop quality permitted.

A smoothed variant of a standard rose diagram is used, where a sliding sector (angular bin) is used to produce a moving average plot (e.g., Figure 3). These are similar to the plots described by Munro and Blenkinsop (2012), except these are not normalized by the sector size. In one degree increments, each ray represents the number of readings 10° either side of that ray, for a total sector span of 20° . This approach reduces the influence that bin boundary position and size has in the resulting standard rose diagrams (Fisher, 1989; Wells, 2000). Additionally, it facilitates statistical modeling described below, in part by retaining the precision lost when a given strike value is “placed” within a standard rose diagram bin. As with standard rose diagrams, distinct preferred orientations result in petals, with the position and width determined by preferred orientation position and variance. Broader and asymmetric petals can result from two closely oriented preferred orientations.

To aid in identification of preferred orientations, resulting sliding sector plots were modeled as a polymodal distribution comprised of up to four normal distributions (for ease and as an approximation to the expected Von Mises distribution) and a uniform component. Initial estimated means, standard deviations, and overall population proportions were input. The resulting model curve is visually compared with the observed curve. Input values are reiteratively changed to minimize the difference between the two (typically a 5% to 15% average ray model vs. observed difference, dependent on the n -value and distribution complexity). In practice the difference is quite sensitive to the mean chosen, with just 1 to 2 degrees making a substantial difference. Data from multiple photographs are aggregated for a given study area. More details are provided in the supporting information and Table 2.

Traverse data, where orientation, position, and other traits are recorded in a measured direction that is often determined by available outcrop exposure, was used. Such data have an inherent directional bias (e.g., Park & West, 2002; Watkins et al., 2015) with preferred orientations subparallel to the outcrop significantly under-represented, a bias partially alleviated by traverses at high angles to each other.

Triassic growth faults (Osmundsen et al., 2014) were opportunistically sampled as encountered in field work. At the SW tip of Edgeøya, exceptional 7–9 km long coastal cliff exposures at Kvalpynten (Figure 2a) trending roughly N-S and EW were a focal study area for the thin-skinned Triassic faults. Data for steeper Triassic, normal faults originate from a more widely distributed area (Figure 2a), with varying cliff and steep slope orientations.

4. Results

4.1. Edgeøya Diabase Sill Joints

Scaled and oriented images were analyzed for the length-weighted strike distribution of joints in horizontal sills at five sites in southern Edgeøya (site info Table 2 and locations in Figure 2). Joints are predominantly sub-vertical, and so the strike distribution is considered sufficient for analysis. Figure 3 and Table 2 provide results for all five sites, examples of analyzed images, and a composite plot and model of data from all five sites.

All sites have modeled preferred orientations $\approx$ E-W and $\approx$ N-S (Table 2). The statistical model for the aggregate data from all five sites has three means (preferred orientations) that make up $>10\%$ of the total, two of which occur at 089° and 169° (Figure 3b, P2 and P3, respectively). Based on observations at individual sites these are considered to be a sub-orthogonal joint pair. At Svarttangen (Figure 3a) the strike distribution is simpler and dominated by this same orthogonal pair. A third, well-defined, significant preferred

Figure 4. (a) Smoothed frequency plot (see y-axis for details) of strike of joint line segments that truncate (in blue) versus those that are truncated (in tan) in the interpreted scaled/oriented photos of diabase joint patterns from southern Edgeøya. Primary data in supplemental document *EdgeøyaDiabaseData.xlsx*. (b) Field photo from Andretangen site of calcite vein along E-W opening mode fracture within the diabase (arrows). N to upper left. Scale in mms. (c) Photomicrograph of calcite vein in diabase. Scale bar 1 mm.

orientation with a modeled strike mean at 023° is evident at four out of the five sites. A fourth and minor direction (only 4% of total population) was modeled in the aggregate data at 139° . At Interior Site 1 the NE-SW and SE-NW directions dominate and a sub-orthogonal relationship between the two is clearer (Figure 3a) with the NE-SW direction dominant.

Joint truncations can provide relative age relationships (Gross, 1993) and were identified in the oriented/scaled photos. Figure 4a shows the smoothed frequency by orientation of truncated (younger) versus truncating (older) joints, along with the directions modeled from the aggregate data plot. There is continuous overlap between the truncated versus truncating populations, excluding a simple interpretation. The complexity may have resulted from multiple directions developing during a jointing episode, as would be expected with cooling, and/or from later reactivation of earlier formed joints. However, significant differences also exist between the two. The 139° and 023° modeled means correspond to a peak of truncated, younger, fractures. The 089° modeled mean correspond to a peak of truncating, older, fractures, and the 169° corresponds to a roughly equal number of truncating and truncated fractures.

Summarizing, the preferred joint directions in southern Edgeøya sills are interpreted as two orthogonal joint pairs: one represented by the 89° and 169° model means and the other by the 023° and 169° model means.

All four directions can be seen at one locality (e.g., Figure 3a, Andretangen and Interior 1 sites). The earlier (based on truncations) $\approx$ E-W and $\approx$ N-S pair have roughly equivalent proportional development. In the later orthogonal pair the 23° direction strongly dominates. Plots and models from individual sites better reflect an orthogonal character (Figure 3a and Table 2), and departures from 90° in the aggregate model are thought to reflect some inter-site variation in joint set orientation along with differential site contribution to the aggregate. The 139° mode makes a significantly smaller contribution (Figure 3b) and is thus considered less constrained.

Aerial images from TopoSvalbard include coverage from large (tens of km²), sub-horizontal sill exposures from (a) the northern tip of Barentsøya, (b) the facing coast of Spitsbergen (Capes Muhry and Weyprecht), and the intervening islands of Alekseevøya and Kukentøya (Figures 1 and 2). These are also visible in Google Earth imagery (the 17 August 2011 image offers the best quality for seeing the joints). These fortuitously display the map pattern of diabase fractures patterns well (Figure 5). The reader is strongly encouraged to explore them in order to better understand the sill joint patterns to a greater depth than possible with the select and smaller example images provided here. Well-developed $\approx$ N-S and $\approx$ E-W trending preferred orientations are readily evident, as are other directions. Three areas were chosen for further analysis: one area where N-S and E-W directions dominate and two others with more complicated patterns. All three areas have modeled strike means oriented $\approx$ E-W and $\approx$ N-S (Figure 5 and Table 2), while other preferred orientations vary by site.

This imagery increases the footprint of earlier formed E-W and N-S orthogonal joint pair significantly. The manifestation of the joint sets as visible topographic features on the imagery is likely a function of the interplay between fracture traits (e.g., length, density, and orientation) and erosional processes (e.g., glacial plucking and scouring, and wave action and coast line orientation). Hence, it is likely that certain directions are locally preferentially expressed. Directions at a high angle to the coastline appear to be favored. The coastlines of Alekseevøya closely match the preferred directions (Figure 5a), suggesting that fracture pattern influences topography over a range of scales.

A well-developed 47° joint mean at Alekseevøya (Figure 5a) is similar to the 50° mean at the Andretangen site in southern Edgeøya (Figure 3). This direction tends to be locally developed and parallel to larger lineaments that cross Alekseevøya (Figure 5a), suggesting a more clustered and less distributed pattern. A 28° direction at Kapp Muhry is also seen in the southern Edgeøya data. While the E-W and N-S orthogonal pair is found at all the study sites, the other preferred directions are more variably expressed suggesting that these latter directions are more domainal. Fracture domains within the sill are apparent to the eye in the imagery (Figure 5).

In southern Edgeøya, especially along sill margins, E-W and N-S opening mode fractures are locally infilled with calcite veins (Figures 4b and 4c). These tend to taper into the interior of the sill and to extend into the host rock. Associated alteration zones that penetrate several millimeters into the diabase contain calcite, actinolite, chlorite, and possibly iddingsite (thin section ID, Figure 4c). Sill interior joints were often relatively smooth without or with only muted ribs, hackle marks, or plumose structures. A low relief of joint surfaces may reflect subcritical growth (Savalli & Engelder, 2005). Near sill margins joint surface features were more visible, perhaps influenced by finer grain size. Orientations suggest radial, vertical, and horizontal fracture propagation directions, with a perceived greater frequency of sub-horizontally oriented ribs. In map view overlapping fracture tips tend to be straight without obvious deflections.

4.2. Joints in Triassic Strata on Edgeøya and Hopen

Figure 6 displays orientation data for joints in Triassic sandstones and shales of the Botneheia through the De Geerdalen formations (Table 1) on Edgeøya. A composite stereonet plot, combining data from Lord (2013) primarily at sites along the northern section of the W coast, and data from this study, mostly at Kvalpynten and sites along the S coast, show a complex polymodal distribution (Figure 6a). Five preferred orientations have been approximated by eye based on the center of data density maxima. In addition, to facilitate comparison, scaled and oriented images of sub-horizontal outcrop surfaces of these Triassic strata were analyzed and modeled in the same way as the diabase (Figure 6d and Table 2).

In both plots (Figures 6a and 6d) an E-W striking orientation is strongly developed, and in the images a subordinate approximately N-S set exists (Figures 6a and 6d). Two other general preferred directions

Figure 5. (a) Interpreted images (N up) and modeled plots of diabase sill fracture lineaments from (a) Alekseevøya, (b) NW coast of Kükenthaløya, and (c) Kapp Muhry just N of Barentsøya. Images taken from the Norsk Polarinstitutt online map server (<http://toposvalbard.npolar.no/?lang=en>). Locations shown in Figure 2b. Colored lines are segments along visible joint traces. For Kapp Muhry the yellow belong to the N-S and EW orthogonal joint pair, and the red to a later preferred orientation. Blue dashed lines in part (a) exemplify two different joint patterns consistent with differing domains contributing to the overall sill pattern. Additional location and plot information in Table 1. Smaller insets show higher resolution versions used in interpretation.

include a more variable NE-SW direction and a subordinate direction $\approx 150^\circ$. Figure 6a shows the $\approx 150^\circ$ direction to be primarily expressed in Lord's (2013) data from NW Edgeøya and absent in the modeled data from southern Edgeøya. Significant differences also exist from site to site in the southern data (Table 2). One shoreline wave-cut platform outcrop exhibited a sharp boundary between two different longitudinal joint directions, indicating a patchwork domainal development of the joint pattern occurs at multiple scales.

In the more massive Tschermakfjellet Formation shales at Kvalpynten there is typically a dominant joint preferred orientation of greater continuity with subordinate directions that abut against the dominant

Figure 6. (a) Lower hemisphere, equal area stereonet plot of poles to 565 joints in host Triassic strata on Edgeøya, with five interpreted preferred directions shown as great circles and poles (red boxes). Red poles from Lord (2013), black poles from this study. Kamb contours of total data (interval 2) using Allmendinger et al. (2011) Stereonet 10 software. (b) Image of closely spaced sub-vertical, N-S trending joints in De Geerdalen Formation shales along Kvalpynten cliffs on Edgeøya, looking NNE. (c) Example of oriented/scaled image interpreted for joint traces from the very base of the Tshermakfjellet Formation and analyzed for fracture strike distribution. (d) Composite sliding sector plot from three sites (Figure 2, additional information in Table 1) in Triassic strata of southern Edgeøya along with input for statistical model.

one. The E-W and/or $\approx 053\text{--}063^\circ$ orientations were typically, but not uniformly (e.g., Figure 6b), the dominant direction observed in the field. Vertical continuity greater than 10 m and horizontal continuity on the order of meters was observed. Spacing was often on the order of 10 cm. Tip curls were uncommon. Locally, the opening mode fractures are very thin (<1 mm) calcite veins instead of simple joints. In the shales joint surfaces often display well-developed surface textures consistent with a radial propagation pattern, or where the lithologic contrast of bedding was greater, bedding-parallel propagation. Relief of surface features (e.g., hackle marks) of up to 1 to 2 cm was observed. Joints in the sandstones and where bedding planes provide a mechanical contrast are both bed constrained and cross-cutting (Lord, 2013).

Figure 7. Sliding sector plot and statistical model of Lord's (2013) data on joints in Triassic strata from Hopen.

Lord (2013) also measured and analyzed joint patterns in Triassic strata of Hopen, where a suite of steep normal faults trending ESE-WNW also occur (discussed below). Using these data and filtering for sub-vertical joint strikes (dips $>75^\circ$) to facilitate comparison, modeling allowed identification of four sub-vertical preferred directions (Figure 7). Since this was data collected along outcrop cliff line traverses, conclusions concerning relative proportions of different preferred orientations in the overall distribution were not drawn. Noticeable in the distribution is the dominant 017° preferred orientation, which is roughly parallel to the elongate direction of the island, suggesting the joint network influenced topographic development. This is also subparallel to a direction seen in the Edgeøya diabases (Figure 3b, P1 at 23°). The 145° preferred orientation is similar to one estimated from the traverse data from Triassic strata on Edgeøya (Figure 6a, $151/331^\circ$). A joint direction with a strike subparallel to that of the Hopen normal faults is distinctly not evident in the structure nor is the common E-W direction seen in Edgeøya.

4.3. Joints in Strata From Southern Spitsbergen

Joint data were also collected from three sites in southern Spitsbergen, and summary results are presented in Figures 8 and 9. Treskelen is the site of the Hyrnefjellet anticline (Figure 8e), within the southern part of the Cenozoic WSFTB. Data were collected from the following four different stratigraphic horizons (Table 1): (a) the Carboniferous Treskelen Formation, (b) the Permian Kapp Starostin Formation, (c) from the middle and top of the Triassic Sassendalen Group, and (d) from near the top of the Triassic-Jurassic Kapp Toscana Group (Ct, Pks, Trs, and Trk respectively in Figure 8e). Results are described in descending stratigraphic order below, and resulting directions are summarized in Table 2.

Appropriate outcrops to take oriented/scaled images of joint traces on bedding surfaces were not found in the Triassic strata at Treskelodden, and so traverse data were collected along bedding $\approx$ strike-parallel outcrop faces. A resulting plot of joint pole orientations when bedding is restored to horizontal (to help determine pre-folding joint positions) documents a somewhat elongate data density concentration (Figure 8a) suggesting two merged pole concentrations. The highest density suggests a pole preferred orientation that is sub-parallel to the Hyrnefjellet anticline fold axis (trend and plunge estimated at 159° and 9° , cylindrical best girdle fit from 49 poles to bedding readings), which is a common joint orientation association for folds (e.g., cross-fold joints, Fossen, 2016). In addition, the cluster elongation toward more N-S poles could be due to a subordinate steep $\approx$ E-W joint set. In addition, there is an orthogonal subordinate pole concentration slightly counterclockwise of E-W, which may reflect an $\approx$ N-S set.

Figure 8b derives from analysis of oriented and scaled images taken perpendicular to the bedding of Kapp Starostin Formation cherts near the peninsular tip at the fold hinge where stratal dips are $<10^\circ$. Four preferred joint trace orientations were modeled. Rotating bedding back to horizontal yields strikes of 006° , 056° , 089° , and 151° (about a 2° difference from unrotated results). These are interpreted as two sub-orthogonal sets of different age, based on outcrop observations. The 89° direction is typically the longitudinal joint, and this direction as well as the 006° set were distinctly infilled by thin (several mm or less) calcite veins, while the other sub-orthogonal set was typically barren (Figure 8c). Joints are planar with little relief, and overlapping tips straight.

Figure 8d was derived from oriented and scaled images perpendicular to bedding of Treskelen Formation orthoquartzites ≈ 50 m N of the Kapp Starostin Formation site discussed above. Three preferred orientations were modeled. Two (Pks/Ct $55^\circ/49^\circ$ and $88^\circ/84^\circ$) are similar to preferred directions modeled for the Kapp Starostin Formation. An N-S counterpart to the direction well developed in the overlying cherts is missing. In addition, the NE-SW and SE-NW trending sets that are subordinate in the Pks cherts dominate in the Ct quartzite. Joint traces are distinctly less continuous and planar in the quartzite in comparison to the chert.

Figure 8. Joint data from Treskelodden, Hornsund. (a) Lower hemisphere contoured plot of poles to joints in Triassic strata, with bedding restored to horizontal. Data from two traverse in the Sassendalen Group and one in the Kapp Toscana Group. Traverses were oriented sub-parallel to bedding strike. (b) Image of E-W and N-S orthogonal joint set in Permian Kapp Starostin Fm. strata and below sliding sector plot with model parameters from oriented image analysis. (c) Image of 3 joint sets in Kapp Starostin Fm. cherts at the very tip of the peninsula. Note calcite veining. Brunton oriented aligned with N to top. (d) Plot of joints for underlying Carboniferous Treskelodden Fm. strata. (e) Measurement sites on simplified geologic map of Svalbard, with fault type unspecified and anticline axial trace shown as dashed line. Map modified from Norsk Polarinstitutt digital geologic map of Svalbard. Map units: C = Carboniferous; P = Permian; Tr = Triassic (multiple units, purple); J = Jurassic; K = Cretaceous. For (b) and (d) bedding dips were small, and data were not reoriented.

Figure 9. Joint data from W coast Sørkapp (Rafenodden) and from valley just east of Lidfjellet. (a) Sliding sector plot and model parameters for Carboniferous strata at Rafenodden. (b) Image looking east along the dominant E-W set at Rafenodden. (c) Sliding sector plot and model parameters for Triassic strata in Liddalen. (d) Photo of sub-horizontal outcrop with three defined joint sets. (e) Measurement sites on simplified geologic map. Color scheme unit designations as in Figure 8e, with Pc as Precambrian basement. Map modified from Norsk Polarinstitutt digital geologic map of Svalbard (<http://svalbardkartet.npolar.no>).

The Sørkapp localities (Rafenodden and Lidfjellet, Figure 9 and Table 2) are located within the hinterland portion of the WSFTB along the Spitsbergen coast (Bergh & Grogan, 2003; Figure 9 and Table 2). At Rafenodden, Carboniferous Billefjorden Group strata are sub-horizontal and offset by normal faults associated with later Cenozoic transtension (Dallmann et al., 1993; Winsnes et al., 1993). Analysis of oriented and scaled images (Figure 9a) documents two well-developed joint preferred orientations of roughly the same contribution to the overall distribution at 011° and 091°, similar to directions seen at Treskelen (Table 2). The 091° trend is the more continuous, longitudinal direction (Figure 9b). Minor SE-NW directions were modeled but are poorly constrained. Feathering of fracture tips and some tip curling toward

adjacent joints was observed. Physical erosion by waves has smoothed exposed joint surfaces so that surface features were difficult to see. The joints typically cut across bedding in these massive orthoquartzites.

Analyzed images from Lidfjellet come from basal Triassic strata within tens of meters of one more continuous N-S normal faults in the area with ≈ 150 m of post-Triassic throw. Sub-horizontal thrust faults in overlying Triassic and Jurassic strata project above the sample outcrops (Dallmann et al., 1993; Winsnes et al., 1993) creating one of the more structurally complex sites in our study. The resulting plot (Figure 9c) is correspondingly more complex and distinct. The dominant modeled trend of 053° is within 5° of the modeled preferred orientation at Treskelodden. The well-developed E-W direction seen at both the other sites is missing at this site, and a well-developed preferred orientation here, modeled at 125° , is missing at the other sites. Fracture tips are straight and do not show curls or deflection. Fracture surface relief is on the order of several mm. In the alternating shale and sandstone beds, joints are most commonly strata-bound.

In summary, for the southern Spitsbergen area, two regional sub-orthogonal pairs are postulated to contribute to local joint patterns. One pair is roughly aligned with the Cenozoic WSFTB folds (NNW-SSE), with a dominant set sub-perpendicular to the fold axis, and is particularly well developed in the Triassic strata. The other sub-orthogonal set is close to N-S and E-W oriented. For two sites (Figures 8b and 9a) the E-W direction is clearly the more continuous set of longitudinal joints (and ostensibly older). Study sites differ substantially in terms of the relative contribution to the total distribution by each of the four different directions, and not every direction is evident at each site. Varying joint surface morphology is associated with different lithologies and bedding thickness.

4.4. Opening Mode Fractures in Diabase Sills and Host Strata of Central Spitsbergen

Considerable fracture analysis has been conducted as part of a carbon dioxide sequestration research project in the Adventdalen area where the target reservoir was within the Late Triassic to Middle Jurassic strata and where diabase sills were encountered in the drill holes (Ogata et al., 2012; Ogata et al., 2014; Senger et al., 2013; Senger, Planke, et al., 2014). In addition, Lord (2013) undertook a fracture analysis that focused on the DeGeerdalen Formation strata in central Spitsbergen. In order to expand regional coverage of joint orientations, the following section reviews the Adventdalen data and reanalyzes some of the published Lord (2013) data.

Ogata et al. (2014) identified five litho-structural units (LSUs), including the diabase sills. For the sills (1,084 orientation measurements) they identify four to five distinct sets where J1, interpreted as the earliest joint set, was slightly counterclockwise of E-W for bed-confined opening mode fractures and E-W for through-going ones (their Figure 7). A sub-orthogonal counterpart (J2as) and three other directions (J2a, J2b, and J2bs) were identified. Similar results were found in the host strata, and their overall conclusion regarding preferred orientations is as follows (Ogata et al., 2014):

Within the analyzed LSUs we identify a main fracture set, J1, comprising systematic joint populations oriented approximately E-W, and a subordinate fracture set, J2, characterized by systematic joint populations oriented approximately N-S. Along with these, a high-angle, conjugate set of shear fractures, S1, trending roughly NE-SW and NW-SE were identified mainly in the coarser-grained and more cemented lithologies, whereas a low-angle, shear fracture set, S2, striking E-W to NW-SE is observed within finer grained lithologies and some igneous intrusions (S2b). (p. 151)

A sliding sector plot of Lord's (2013) joint data from DeGeerdalen Formation strata in central Spitsbergen (Figure 10 and Table 2) appears as a quite broad sub-orthogonal pair of preferred orientations. However, the interpretation of two sub-orthogonal overlapping preferred orientations in southern Spitsbergen (Figure 8) and subtleties in the distribution shape (significant petal asymmetry) suggest a more complex distribution. Modeling results in two sub-orthogonal pairs: one at 090° and 178° and the other at 068° and 154° . These preferred orientations are similar to those determined in Ogata et al. (2014) for Triassic strata in the area.

4.5. Triassic Fault Traits on Edgeøya, Hopen, and Offshore

Syn-sedimentary Triassic normal faults on Edgeøya and Hopen (Braathen, Midtkandal, et al., 2017; Maher et al., 2016; Ogata et al., 2018; Osmundsen et al., 2014; Smyrak-Sikora et al., 2018), and offshore

Figure 10. Aggregate sliding sector plot (similar parameters to those above, $n=358$) of joint strikes from Lord (2013) for central Spitsbergen (red line) along with model distribution (blue line). Input parameters for model below.

(Anell et al., 2013), provide potential insight into crustal stresses at that time. These faults can be separated into two groups, thick-skinned versus thin-skinned, a division introduced by Anell et al. (2013) and adhered to herein. A similarly oriented normal fault occurs in Triassic strata on Barentsøya (Winsnes & Worsley, 1981), further increasing the regional footprint of this deformation (Figure 2). While Cretaceous sills and Triassic faults occur in relative proximity (the same cliff side) outcrops with interactions between them were not found.

4.5.1. Steep, planar faults

The W-facing cliffs of Schwarzpynten and Tjuvfjordhorga (SE end of Edgeøya) display more than 20 relatively planar faults within De Geerdalen Formation strata over a distance of some 15 km (Ogata et al., 2018). Most of the faults dip SW and have throws on the order of meters to tens of meters (Figure 11a). A lack of distinctive marker beds within the DeGeerdalen Formation strata makes the faults harder to discern, requiring careful inspection. Striae are primarily dip-slip (Figure 11d). Upward fault truncation within the sequence, stratigraphic thickness changes across faults, and stratal onlap on tilted layers all indicate syn-sedimentary movement. At Schwarzpynten (Figure 2) onlap was observed within the Tschermakfjellet Formation shales, and thickness changes and fault truncation occur within the DeGeerdalen Fm. strata (Figure 11a), while other faults cut the entire exposed section. Stepped throw gradients are also consistent with polyphase, syn-sedimentary movement. At E Skrinnehovden (Figure 2a), Tschermakfjellet Formation shales onlap an $\approx 100^\circ$ striking fault monocline within the Botneheia Formation (Figure 11c). Distributed normal faulting in the monocline limb indicates extension, consistent with the development of a tri-shear zone (Fossen, 2016) above a fault tip. Other clear examples of syn-sedimentary movement along these faults exist on Edgeøya (Ogata et al., 2018; Osmundsen et al., 2014; Smyrak-Sikora et al., 2019).

On Hopen lateral thickness changes within the Flatsalen Formation (above the DeGeerdalen Fm, Table 1) occur across a monocline that lies above one of the normal faults, indicating continued syn-sedimentary faulting higher in the stratigraphic succession than that observed on Edgeøya. The faults on Hopen have a similar ESE-WNW trend to those on Edgeøya (Figure 11d). Anell et al. (2013) describe faults with similar trends on the Hopen High that are evident in offshore seismic sections. These faults root into the basement, cut up through the Triassic, and show seismic-scale thickness changes in the Permo-Carboniferous section. They conclude that a mild Triassic extension phase that reactivated deeper faults can be documented offshore.

In summary, steeply dipping normal faults are widely distributed in SE Svalbard with a ESE-WNW trend and up to decameter throws. On Edgeøya they are preferentially down thrown to the S, as are possible offshore equivalents (Anell et al., 2016). There is evidence for syn-sedimentary fault movements during deposition of the upper Botneheia Formation through the DeGeerdalen and Flatsalen formations. Given that an individual fault on Edgeøya with evidence for syn-sedimentary movement during deposition of the Botneheia Formation time also cuts DeGeerdalen Formation strata at a higher level, fault reactivation must have occurred over a substantial length of time (>10 Ma). Overall, $\approx$ NNE-SSW normal faulting-related extension would be most consistent with the σ_2 and σ_{mh} principal stress oriented in an $\approx$ WNW-ESE orientation. Average fault spacing on Hopen and SE Edgeøya is 2.4 km and 750 m, respectively. With throws of meters to decameters the distributed extension is likely ~ 0.01 or less.

4.5.2. Thin-Skinned Faulting and Basins

Edwards (1976) first noted growth faults and basins within the Triassic sequence exposed in the extensive cliff exposures of Kvalpynten and attributed them to gravitational collapse of a delta front. Similar growth faults and basins occur at several other localities, including the NE part of Edgeøya (Figure 2a), establishing a significant footprint for these features. Anell et al. (2013) and Osmundsen et al. (2014) provide more

Figure 11. Data for steep Triassic faults. (a) Photointerpretation of portion of Schwarzpynten western cliffs looking east. Red dashed lines are faults and colored lines trace distinctive horizons, the lower most of which is the approximate contact between the underlying Tschermakfjellet Fm. and overlying DeGeerdalen Fm. Cliffs are approximately 300 m high, and approximate midpoint of photo at 77.29° and 22.54° . (b) Trace of Hopen and normal faults, from Mørk et al. (2013). (c) Interpreted image of monocline in Bothneha Fm. strata (Trb) onlapped by Tschermakfjellet Fm. strata at East Skrinhovden (Figure 2). Inset is of small normal faults that characterize the monocline limb. (d) Stereonet plot of fault planes ($n = 55$) and associated fault striae ($n = 49$), along with striae Kamb contours with a interval of 2 standard deviations. Readings are from both Hopen and south Edgeøya.

detailed description, arguing that there was a tectonic influence. Braathen, Midtkandal, et al. (2017) argue that differential delta-front compaction was involved, a model that Ogata et al. (2018) and Smyrak-Sikora et al. (Smyrak-Sikora et al., 2019) elaborate on.

Truncation of the faults by a draping sandstone of the De Geerdalen Formation and truncation of faults within the underlying Tschermakfjellet Formation indicate a complex polyphase development history (Figure 12). Listric faults, wedge shaped fill geometries, and exposed structures indicate a detachment exists approximately at the base of the Tschermakfjellet shales or within the top of the Botneheia Formation, probably due to early cementation of the Botneheia Formation shales (Krajewski, 2008) that provided a strength

Figure 12. Data for thin-skinned syn-sedimentary Triassic faults. (a) Fault data from Kvalpynten area (Figure 2a). Contoured (Kamb contour interval of 3 standard deviations) poles to fault planes ($n = 175$, best fit girdle striking 36°) in black and contoured fault striae ($n = 139$) in red. (b) Plot of rotated bedding from Kvalpynten ($n = 68$) with best fit girdle striking 38° . Kamb contour of two standard deviations. (c) Structural data from Tjuvfjordskåda (Figure 2); 19 poles to bedding in blue with a best fit rotation axis of $126^\circ-1^\circ$, fault planes in red, oscillation ripple marks in green. (d) Interpreted photo mosaic from N end of Kvalpynten showing the polyphase syn-sedimentary and low-angle normal faults (black). Yellow and red lines trace distinctive horizons in the Tschermakfjellet and DeGeerdalen formations. The continuous fault draping sandstone is roughly 200 m above sea level.

contrast. Significant soft-sediment deformation, including sandstone dikes, is consistent with syn-sedimentary faulting, but the detachment level also shows brittle features and distinctive mineralization (i.e., cone-in-cone calcite growths) indicating faulting occurred during early lithification (Maher et al., 2016; Ogata et al., 2018). Conjugate fault planes, fault striae, and the rotation of strata (Figures 12a–12c) show significant dispersion, but all indicate a dominant general NE-SW extension for the Kvalpynten area. Data are from both the more N-S and E-W-oriented cliffs. Older faults in the Tschermakfjellet Formation shales tend to be N and S dipping, but faulting associated with the overlying sandstone dominated basins are primarily S dipping (Figure 12d).

Similar basins also occur at Tjuvfjordskarvet (Figure 2) to the E, but exposures are of much lower quality. The limited structural data obtained are consistent with NE-SW extension and dominant SW dipping normal faults (Figure 12c). Osmundsen et al. (2014) reviewed other Edgeøya localities to the N with skin-thinned faulting and half graben development, such as at Skrukkefjellet and Klinkhamaren, and transport directions are predominantly to the SW or SSW, indicating regionally coherent kinematics. The similarity in orientation, in asymmetry (predominantly S dipping for later growth basin development), and overlap in timing all indicate that the thick- and thin-skinned normal faulting are in some manner related. The easiest explanation is that regional tilting, and perhaps seismic events, associated with the prior, helped destabilize delta-front Tschermakfjellet shales, with differential compaction and faulting above or just within lithified and stronger Botneheia Formation shales (Braathen, Midtkandal, et al., 2017; Ogata et al., 2018; Osmundsen et al., 2014).

5. Discussion

Recognition of cooling fractures that were oriented by the existing regional stress field in the Cretaceous diabase sills helps to constrain interpretations of other opening mode fractures in the intrusives and host

strata. Therefore, this topic is discussed first. The existence of similarly oriented regional tensile fracture sets in the host Triassic strata, along with a consideration of potential loading paths, suggests that HALIP was associated with an Early Cretaceous regional jointing episode, and this topic is addressed next. Possible relationships of those regional joint sets with the tectonic setting and regional stress field are subsequently explored. To then understand the evolution of the regional stress field, the Triassic, Cretaceous, and Cenozoic structural patterns are compared. The history of the regional fracture patterns and causative stress fields is complex and will need more investigation, but a summary working model is proposed.

5.1. Diabase Cooling Joints and the Regional Cretaceous Stress Field

Cooling fractures due to thermal contraction are a ubiquitous and expected feature in intrusive bodies and perhaps have been most clearly recognized and studied in granites (Bankwitz et al., 2004; Martel & Bergbauer, 1997). In granites more easily datable material can fill early opening mode fractures and better constrain timing. Mafic lava flows and sills are also well known to display cooling-related joints (e.g., Monreal et al., 2009; Senger et al., 2015). Jaeger (1961) estimates that columnar joints start forming at $\approx 60\%$ of the original magma temperature. Bankwitz et al. (2004) also argue for the formation of joints during cooling of granites at high temperatures. Given expected cooling rates, the joints would form very soon after crystallization, which for these HALIP associated intrusion was ca. 124 Ma (Corfu et al., 2013; Senger, Tveranger, et al., 2014). A complete absence of cooling joints would be difficult to explain.

In horizontal sills the cooling strain would be expected to be horizontally isotropic, resulting in multiple joint preferred orientations, without one joint direction dominating (although later reactivation of one set could alter this relationship). Given this consideration, an initial interpretation of an equally developed, lone orthogonal joint pair in a sill is that these are cooling joints. The $\approx$ N-S and $\approx$ E-W regional joint pair in the eastern Svalbard sites (Figures 3, 5, and Table 2) are interpreted to be such cooling joints oriented by the regional stress field. Their ubiquitous distribution (found at all the study sites) and common overall roughly proportional development are consistent with such an origin. This interpretation is also supported by the occurrence of veins with the same orientation that are concentrated at the sill margins. The mineralogy and associated diabase alteration (Figures 4b and 4c) are attributed to hydrothermal activity during cooling, as the opening mode fractures allowed fluids access to the sill margins and the temperature differences drove fluid flow. The association with sill margins and a lack of evidence for an independent post-HALIP hydrothermal event in the Triassic strata of the Edgeøya area support an intrusion-related origin.

Given that a preexisting joint can inhibit subsequent joint propagation, at T junctions the truncated joint should post-date the truncating joint. For a tetragonal cooling pair of joints (Aydin & Degraff, 1988), mutual truncating and truncated relationships should be observed between the joint pairs. While complex, the distribution of truncated versus truncating joints in the oriented/scaled images (Figure 4a) shows differences consistent with the E-W and N-S joint directions predating other preferred orientations, an age relationship clearest for the E-W set.

Cooling and/or shrinkage fractures may be expected to be polygonal and random/uniform in their strike distribution. However, they are known to show a diversity of patterns including tetragonal (Aydin & DeGraff, 1988). For columnar jointing the tetragonal pattern is often associated with flow margins and rapid cooling by water (Gudmundsson, 2011, pp. 325–326). Another possibility is that opening mode fractures driven by volume shrinkage can be organized by an extant regional or local stress fields into two consistent orthogonal directions. Examples include coal cleats (Engelder & Whitaker, 2006; Laubach et al., 2006; Olson et al., 2009) and chalcedony veins (Maher & Shuster, 2012). In this way, fracture loading is not directly driven by the tectonic stress fields but indirectly records them. This phenomenon could occur in the subsurface where the regional stress field may be “felt” but would not be expected within surface flows. It would also produce preferred orientations at larger, up to regional scales, whereas other processes may account for organization of joints into a local, patchwork, tetragonal pattern. For example, the occurrence of magma fingers known from some sill margins (e.g., Galland et al., 2019; Schofield et al., 2010) could produce both local non-tabular margin geometries and subtle internal fabrics, both of which could play a role in producing localized and in places concentric fracture patterns. Magma fingers are presently unreported from Svalbard HALIP sills and were not observed during field work.

Given the extent of the common E-W and N-S preferred orientations seen in the Edgeøya sill data (Figure 3), in satellite images from the northern Barentsøya area 160 km to the NW (Figure 5), and in central Spitsbergen (Ogata et al., 2014), these orientations have a large footprint and thus are thought to reflect a regional stress field. In summary, we propose that horizontal principal stresses were aligned roughly E-W and N-S during sill cooling.

Based on the cooling joint orientations within the sills alone it is unclear which principal stress was associated with which tetragonal joint direction. The T-junction truncation data does show the E-W joints to be more consistently earlier (truncating). On a speculative note, this may be explained if an N-S extension and least principal stress direction caused the E-W oriented of cooling joints to propagate faster than its counterpart of the tetragonal pair.

The dominance of sub-horizontal sills and relative paucity of dikes on Svalbard would suggest that σ_3 was sub-vertical at the time of intrusion and therefore the crust in a state of horizontal compression. However, sills are known from extensional regimes (e.g., the Palisades sill, Herman, 2005), and the role of anisotropy and the influence of the magmatic pressure and local intrusion-related stresses complicate a simple interpretation (e.g., Stephens et al., 2017). In any case, cooling-related contraction in the sub-horizontal sill would generate localized horizontal tensile stresses that would cause a horizontal σ_3 within the sill and sub-vertical cooling joints aligned with the regional maximum horizontal stress (σ_1 or σ_2) to form.

5.2. Development of a Regional Cretaceous Joint Set

Joint orientation distributions in the host Triassic strata of Edgeøya are more complex than in the diabase intrusions, possibly because of a lower tensile strength and associated threshold for fracturing. However, a consistent, E-W direction exists with a subordinate N-S counterpart (Figure 6, Table 2). These were observed to occur in the form of a longitudinal and cross joint pair (e.g., Figure 6c). The simplest interpretation is that these opening mode fractures were generated in the same regional stress field that organized the cooling fractures in the diabase. Locally, some of the same veins in the margin of the sills continue into the host Triassic strata (e.g., at Andretangen, Figure 2), consistent with local development of opening mode fractures with this orientation shortly after emplacement due to heating/baking and cooling of the rocks at the sill margins. The longitudinal character and dominance of the E-W direction over the N-S direction in the orthogonal pair suggests that the σ_{mh} was oriented E-W at the time. Significantly, these directions are also evident in the platform cover strata of southern and central Spitsbergen (Figures 8, 9, 10, and Table 2), although they are sometimes obscured by overprinting Cenozoic deformation or locally absent.

The fact that the proposed regional Cretaceous opening mode fracture sets are not seen or well expressed in Triassic strata at all sites, for example, at Hopen, may reflect a domainal character to the joint pattern, and/or local anomalies. Such variable expression could be due to some combination of spatially varying lithology (Laubach et al., 2009), differential presence and influence of sills (discussed further below), localized geohydrologic conditions, the previous fracture history, and joint clustering (e.g., Gillespie et al., 2001). In this framework Ogata et al. (2014) identify fracture “corridors” from central Spitsbergen. Determinants of domain patterns, scales, and causes is a likely fruitful research avenue but is beyond the scope of this paper.

Several potential loading paths may have induced Cretaceous regional jointing during sill emplacement and related HALIP activity. First, the complex thermal history of host strata adjacent to intrusion would not only produce a cooling and contraction phase but could significantly alter fluid pressures and fluid flow (Delaney, 1982). Abundant and thick shale layers (Rød et al., 2014) could produce confinement aiding thermopressuring. Brekke et al. (2014), in studying the thermal maturation of Triassic Botneheia Formation strata on Edgeøya, note an advanced maturity given the likely burial history, which they attribute to the proximity of Cretaceous sills. T_{max} temperatures are estimated to be in the 457–470 °C range. Relevant samples with such enhanced maturity cover a 150 m stratigraphic span. Any sill that contributed to the maturity is buried beneath sea level, implying that thermal effects of the sills propagated significant distances into the surrounding strata. Senger et al. (Senger, Planke, et al., 2014) also studied the thermal effects of a 2.28 m thick sill encountered in a drill hole in central Spitsbergen and concluded that contact metamorphism extended into the host rock 165% to 190% of the sill thickness. Enhanced fracturing and mineralization is associated with the sill margins as a consequence of sill cooling. Dypvik (1979) also describes sill-related geochemical changes in Triassic strata 100 m away from a 55 m thick sill. Haile et al. (2019) identify sill-related

hydrothermally induced diagenesis in Triassic rocks on Wilhelmøya, N of Edgeøya, at a distance more than five times the sill thickness. Polteau et al. (2016) explore and model how HALIP could have been a significant catagenic event in the northern Barents Sea area. While mineralogic and visible lithologic changes associated with contact metamorphism are more intrusion proximal, the overall thermal imprint is larger, and sill emplacement could have induced fracturing in a significant volume of rock.

Another potential loading path associated with HALIP and Amerasian Basin development is related to the multistage preferential uplift and erosion in northern Svalbard. This produced a regional Early Cretaceous regression culminating in the deposition of terrestrial Helvetiafjellet Formation facies (Table 1), and subsequently an unconformity between the Early Cretaceous strata and Cenozoic foreland basin sediments (Grundvåg et al., 2017; Maher, 2001; Senger, Tveranger, et al., 2014). Dorr et al. (2012) used apatite fission track data from an ≈ 150 km transect across northern Svalbard to conclude that 2 to 3 km of exhumation occurred between the Early Jurassic and Late Cretaceous. For Nordauslandet, farthest removed from the effects of the WSFTB, five of the seven model ages are between 114 and 133 Ma, roughly coeval with HALIP (Corfu et al., 2013), and the remaining two are older.

Erosional unloading and cooling can cause perpendicular regional joint sets that reflect the regional stress field (e.g., Engelder, 1985; Fossen, 2016, p. 161). Post-HALIP Aptian-Albian Carolinefjellet Formation Cretaceous shorelines and isopach contours trend NE-SW to ENE-WSW in broad alignment, but somewhat counterclockwise to the regional E-W joint set. Such unloading joints could be significantly younger (Late Cretaceous) than those directly associated with local sill emplacement (≈ 120 – 125 Ma). Thus, regional Cretaceous jointing may have been prolonged, polyphase, and polygenetic. Future work may look for subtle differences in directions (e.g., from E-W to counterclockwise of that) and traits that may provide further insight into Svalbard's evolving regional stress field during the late Cretaceous, and to help evaluate ideas of sill related versus erosional unloading as drivers of joint formation.

HALIP-related igneous and deformation activity is distinctly more pervasive in the Franz Josef Land area to the E of Svalbard (Amundsen et al., 1998; Dibner, 1998; Kairanov et al., 2018), and dike suites swarms occur. A preferred dike orientation strikes $\approx 135^\circ$, parallel to a common local fault trend (e.g., in Dibner, 1988, Figure 5.9, p. 116). A subordinate dike direction sub-orthogonal to $\approx 135^\circ$ comprises 10% of the dike suite. These orthogonal directions are counterclockwise from those diabase sill cooling fracture sets seen on Edgeøya, and the difference may reflect regional bending of the stress field trajectories or a changing strike of a consistent direction due to the Earth's curvature (e.g., Wdowinski, 1998). While sills dominate in the Svalbard area, infrequent dikes also occur (Senger, Tveranger, et al., 2014) and provide insight into crustal stresses. Stephens et al. (2017) argue that the geometry of sill-dike complexes can reflect the interplay between far-field stresses and local emplacement-related stresses. They also note that sills, inclined sheets, and dykes can be hybrid shear-dilation fractures. As such the inferred σ_1 and σ_3 change from being parallel and perpendicular, respectively, to a simple opening mode fracture to being oblique for shear fractures, which complicates interpretation. Cretaceous dikes on Edgeøya emanate from sills and are often inclined. Detailed future work on the dikes should provide more insight but is beyond the scope of this study.

Grogan et al. (1999) describe mild compressional inversion within the Late Jurassic strata of the Kong Karls Land Platform to the E of Svalbard. Recent work by Kairanov et al. (2018) uses core and 2-D seismic data to identify a suite of faults reactivated during the Cretaceous (Hauterivian to Early Barremian) in the area to the NE between Svalbard and Franz Josef Land. These were reactivated as reverse faults and trend $\approx 30^\circ$, some 60° from the dominant joint direction seen in the Edgeøya area. Given that these faults are reactivated and any possible strike-slip component is unconstrained, an E-W maximum principal stress could explain both the joints and the reactivated faults. If this compressional deformation regime extended W into the Svalbard area, then the σ_{mh} would also be σ_1 , consistent with sill formation.

Schiffer et al. (2017) modeled the orientations of stress fields in the High Arctic based on present crustal and lithosphere-asthenosphere boundary geometries and the resulting calculated geopotential field. They then compare their model results to stress directions inferred from dike swarm and rift orientations. A primary conclusion is that for many areas the present day stress field was established in the Mesozoic. The onset of this stress field may have induced regional jointing as one mechanism of adjustment of the plate interior to new boundary conditions (Sandiford, 2010). Schiffer et al. (2017) note a misfit between the NE-SW σ_{mh}

direction from the model and the present day stress field and past indicators, indicating this is an area of complexity. An NE-SW direction is, however, a preferred orientation seen in the joint data sets (Table 2).

5.3. Regional Triassic Stress Field

In the Svalbard area, the Triassic was a time of relative tectonic quiescence, continuous subsidence and platform sedimentation, with a large deltaic and coastal plain progradation to the W that was largely sourced by the Urals (Anell et al., 2014; Riis et al., 2008), a shoreline preserved in strata of western Spitsbergen associated with a limited Greenland source area, and a possible northern source in the late Triassic (Worsley, 2008). However, plate margin tectonics can produce mild, but sustained, deformation well into a plate interior (e.g., Sandiford, 2010), often reactivating older elements. In the Edgeøya, Hopen, and offshore areas the above described syn-sedimentary faulting during deposition of Botneheia through DeGeerdalen formations ostensibly provides an example of such intraplate deformation. The data herein helps confirm the conclusion of Anell et al. (2013) that a regional footprint of syn-sedimentary normal faulting (Figure 2) with consistent kinematics (Figures 11 and 12) reflect a Triassic, NW-SE to WNW-ESE regional σ_{mh} . Anell et al. (2013) note that such a direction is at a high angle to the Novaya Zemlya portion of the Urals, which was an active plate boundary at the time (Ritzmann & Faleide, 2009). The situation could be somewhat similar with the Alps and the Himalayas, where highly oblique extension penetrated into an intraplate position. On a speculative note, sinistral transpression is argued to have characterized the Triassic Novaya Zemlya tectonism (e.g., Puchkov, 2012), and the NW-SE to WNW-ESE σ_{mh} suggested herein is oblique to the orogenic trace in a manner consistent with such kinematics.

Olaussen et al. (2019) describe long amplitude, weak, NE-SW trending folding of Jurassic age in the area of Kong Karls Land in eastern most Svalbard. They also relate a Triassic tectonic megasequence in the Svalbard area to the development of the Novaya Zemlya fold-thrust belt. Broadly, the folding is consistent with the NW-SE σ_{mh} proposed above, although the associated deformation regimes differ. Intriguingly, Mulrooney et al. (2018) and Serck et al. (2017) document Triassic growth faulting in this direction for the SW Barents Shelf.

A contemporaneous Triassic joint set would be expected to trend subparallel to the normal faults. The most likely reason for the distinct absence of such a direction in the Edgeøya data is that during sedimentation and early burial the appropriate loading path did not exist and/or sufficient consolidation had not taken place.

5.4. Tertiary Opening Mode Fractures

Given the development of the WSFTB associated with dextral transpression and attendant erosional unloading, and subsequent transtension and development of oceanic crust to the W, Cenozoic joint sets are to be expected. The data from S Spitsbergen (Figures 8 and 9) from strata directly involved in the folding and thrusting show an aligned, often asymmetrically developed, orthogonal joint pair, with the dominant set perpendicular to the fold axis, and a subordinate member containing the fold axis and sub-perpendicular to bedding. An inferred σ_{mh}/σ_1 for the former trends 50–60°, consistent with that associated with fold development and crustal shortening (e.g., Bergh & Grogan, 2003; Braathen & Bergh, 1995). Alignment alone is insufficient to establish these joints formed coevally with Cenozoic deformation. However, given the previous work (described below) and the general association of uplift and unloading with joint formation, and for the purposes of a parsimonious working model, it is considered reasonable to propose that they did so. Such a direction is generally inconsistent with dextral transpression, and likely reflects transpressive decoupling (Bergh & Grogan, 2003; Leever et al., 2011; Lepvrier, 1990; Maher et al., 1997; Maher & Craddock, 1988). During decoupling large weak transcurrent faults can act as “filters,” so only the fault orthogonal component is transmitted into the plate interior (e.g., Van der Pluijm et al., 1997).

However, well-developed NNE-SSW joint directions are also found in data from some of the Edgeøya diabase sites (Figures 3 and 5), Hopen Triassic strata (Figure 7) data, and possibly Edgeøya Triassic strata (Figure 6a). This preferred orientation also occurs in both the diabase and Triassic strata of the central Spitsbergen area (Ogata et al., 2014—their J2b set). Leprevier (1990) and Gabrielsen et al. (1992) describe a complicated structural pattern and history evident in the Cenozoic fill of the Forlandsundet graben (Figure 13a) in the hinterland portion of the WSFTB, and where the age of jointing is constrained as Cenozoic. Leprevier (1990) documents an earlier faulting phase with 20° trend of maximum horizontal compression. Gabrielsen et al. (1992) document a dominant NNE-SSW trending sub-vertical joint set, in Tertiary

Figure 13. (a) Summary plot of preferred orientation of joints. Dashed lines areas covered in previous studies. (b–d) Summary model for stress field evolution in the Svalbard area based on diagram from Torsvik and Cocks (2016).

strata (Figure 13a). This direction is also roughly aligned with the stress field modeled by Schiffer et al. (2017) and would be consistent with coupled dextral transpression.

Kleinspehn and Teyssier (2016) considered the structural evolution of the Cenozoic fill in the Forlandsundet Graben (Figure 13a) and propose Late Eocene WSW-ENE shortening that evolved to NW-SE oblique divergence in the period between 38 and 31 Ma, marking the transition from transpression to oblique divergence. Kleinspehn et al. (1989) use the stratigraphic position and kinematics of small scale faults in Cretaceous and Tertiary strata of central Spitsbergen to develop Svalbard's Tertiary paleo-stress/kinematic history using a back-stripping approach. Their four stage history includes (oldest to youngest): (a) coupled dextral transpression, (b) coupled sinistral transpression, (c) decoupled transpression (WSTFB aligned), and (d) dextral trans-tension. Although a robust result of their analysis, there is presently little evidence for larger structures

associated with the sinistral phase (except, perhaps a sinistral movement phase associated with the SEDL (Svartfjella Eidembukta Daudmannsodden Lineament) zone along the W coast, Maher et al., 1997). Piepjohn et al. (2019) also argue for sinistral movement along the Lomfjorden Fault Zone in eastern Spitsbergen. Thus, for western Svalbard the Cenozoic was a time of significant stress field change with localized variation.

5.5. Summary Working Model

Given the above, the following working model for the evolution of the maximum horizontal stress (the component that can be constrained by sub-vertical joints) in the Svalbard area is proposed (Figures 13b–13d). Deformation regimes, as defined by the orientation of σ_1 and σ_3 , also changed, but for some phases are less constrained. During the Middle Triassic the σ_{mh}/σ_2 trended $\approx$ NW-SE and was primarily driven by the Uralide plate deformation to the E, with a very low-strain extensional regime in the Svalbard area. σ_{mh} shifted counterclockwise to a more E-W trend during the Early Cretaceous when HALIP-related activity and the development of the Amerasian Basin to the N occurred. Kairanov et al. (2018) argue for dextral shear along the Lomonosov ridge during mild Cretaceous reactivation to the NE of Edgeøya. A regional E-W σ_1 could broadly produce a dextral shear component along the Lomonosov ridge (Figure 13c). A continued counter clockwise shift occurred to $\approx$ NNE-SSW trend during the early Cenozoic, a position generally consistent with the coupled dextral transpression between Greenland and Svalbard (Figure 13d). During development of decoupling σ_{mh} was locally reoriented roughly NE-SW in the vicinity of the WSFTB. Due to plate boundary proximity, a complicated history of coupled and decoupled transpression (e.g., Braathen et al., 1999), and the transition to transtension, W Svalbard's regional stress field was more locally diverse and swiftly evolving in the Cenozoic than in the Mesozoic. The counterclockwise rotation with time may reflect a change in which plate margin influenced internal stresses. Initial influence of the Uralide boundary to the E was followed by that of the developing Amerasian boundary to the N, and then by subsequent development of the dextral transpressive, then transtensive transform to the W. While the Cenozoic history is better constrained by the literature, the earlier history in this working model will benefit from continued work. Careful attention to the joint fractography may be particularly fruitful.

6. Conclusions

A sub-orthogonal $\approx$ E-W and $\approx$ N-S joint pair has a regional expression in Svalbard. The nature of their expression in HALIP-related (ca. 124 Ma) diabase sills suggests organization by the regional stress field during cooling. In host strata the Cretaceous regional jointing was possibly driven by associated erosional uplift and unloading on the margin of the evolving Amerasian Basin and/or by the earlier and more direct influence of magmatic intrusions on pore pressures in hydraulically tight strata. In host Triassic strata the EW set dominates the orthogonal pair. The inferred Cretaceous σ_{mh} (maximum horizontal stress) is $\approx$ E-W and the associated deformation regime both uncertain and possibly regionally variable.

Earlier Triassic syn-sedimentary faulting in the Edgeøya area indicates that the σ_{mh}/σ_2 was oriented in an NW-SE to WNW-ESE direction from the Ladinian to the Norian and in a limited-strain extensional regime. A corresponding associated regional joint set in the host strata is missing, likely because of a lack of an appropriate loading path. Based on examples such as the Rhine graben and the Alps, the active Uralian orogeny to the E is a possible driver of this stress field.

Together, the fracture systems suggest a changing Mesozoic regional stress field characterized by counter clockwise rotation of principal stress directions, a change that may have continued into the Cenozoic as the dextral transpressive then transtensive boundary between Svalbard and Greenland developed. An NNE-SSW direction seen in several of the data sets (including in Edgeøya) may be associated with a coupled phase of dextral motion along the Cenozoic plate boundary to the W, while joints closely aligned with the fold-thrust structures may reflect a phase of decoupling.

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