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Episodes of post-Caledonian burial and exhumation in Greenland and Fennoscandia

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A B S T R A C T

The forces that drive uplift of the continental lithosphere outside collision zones are a topic of considerable dispute. Here we review our studies of the post-Caledonian development of Greenland, Fennoscandia and adjacent regions based on apatite fission-track analysis (AFTA) and stratigraphic landscape analysis (SLA). AFTA defines episodes of cooling (exhumation) while SLA provides a relative denudation chronology. Integrating these results with the geological record can produce a coherent history of both positive and negative vertical crustal movements. Our studies reveal a history involving multiple regional episodes of burial and exhumation, leading to a) formation of peneplains graded to sea level, b) formation of distinct unconformities in sedimentary successions, and c) deposition of thick siliciclastic wedges in basins adjacent to the uplifting landmasses. Exhumation episodes which began in late Carboniferous, Middle Triassic and Middle Jurassic affected the entire study area (with some time variations). These episodes correlate with rifting episodes during the break-up of Pangea, attributed to accumulation of mantle heat beneath the supercontinent. Mid-Cretaceous exhumation affected wide parts of the study area and coincided with the inversion of the Sorgenfrei-Tornquist Zone in southern Scandinavia. This may be linked with changes in the relative motion between the European and African plates in the earliest Late Cretaceous. Maastrichtian exhumation affected wide areas around Greenland, probably reflecting doming above the rising Iceland Plume upon its arrival in the upper mantle, prior to the mid-Paleocene impact at the base of the lithosphere. The mid-Paleocene impact of the plume under Greenland contributed to the onset of sea-floor spreading west of Greenland. This represents the onset of the Eurekan Orogeny which affected wide areas around northern Greenland. End-Eocene exhumation interrupted the Eocene regime of subsidence following earliest Eocene break-up in the North-East Atlantic, coincided with a minimum rate of sea-floor spreading in the North-East Atlantic, possibly related to changes in the motion of Africa relative to Europe. Early Miocene exhumation affected only Fennoscandia and is attributed to intraplate stress transmitted across the Eurasian plate. Late Miocene uplift initiated the formation of Greenland's coastal mountains but did not affect Fennoscandia. This episode correlates with changes in the absolute motion of the North American Plate. Pliocene uplift – amplified by the isostatic response to erosion – raised all margins in the region with maximum elevations reached in coastal areas close to Iceland. This suggests support from the Iceland Plume due to outward-flowing asthenosphere extending beneath the conjugate margins of the North-East Atlantic. We use these observations to argue that these episodes reflect both lithospheric and sub-lithospheric forces, related either to changes in the motion of the plates caused by far-field stress induced by events outside the study area, or driven by movements within the mantle directly within the study area. Geodynamic modelling is required to obtain further insights into the properties of the Earth that allow recurrent episodes of uplift and subsidence of the continents.

1. Introduction

Episodes of kilometer-scale burial and exhumation in regions far from active collision zones are well documented, but the nature of the underlying processes remains enigmatic. A key step in understanding these movements is defining their effects in time and space. Central to this is recognizing missing section; i.e. rock sequences that were once present but have been subsequently removed. This phenomenon is manifest by time intervals that are not represented in the preserved rock record – unconformities or hiatuses (Green et al., 2022a).

Our early studies focused on Neogene uplift around the North-East Atlantic (Japsen and Chalmers, 2000). However, our more recent work in Greenland and Fennoscandia (Norway, Sweden and Finland) and adjacent regions (Figs. 1, 2), has revealed multiple episodes of kilometer-scale burial and exhumation of regional extent (Figs. 3, 4) following the early Devonian collapse of the Caledonian mountains in East Greenland and Scandinavia (references listed in Section 3). These episodes occur both before and after the earliest Eocene break-up in the North-East Atlantic (Gee et al., 2008; Gaina et al., 2017). We restrict discussion here to results from our own studies to ensure consistency of approach. We have discussed thermochronology studies across the region from other groups and compared those results with our own in our

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previous publications and these studies are not discussed further here.

Our studies integrate apatite fission-track analysis (AFTA) which defines episodes of cooling (exhumation) and stratigraphic landscape analysis (SLA) which provides a denudation chronology, with the geological record to produce a coherent history of positive and negative vertical movements (Green et al., 2013; Lidmar-Bergström et al., 2013). These episodes led to formation of peneplains graded to the level of the adjacent ocean (and to the subsequent uplift of these peneplains), to formation of distinct unconformities in sedimentary successions and to the deposition of thick siliciclastic wedges in basins adjacent to the uplifting landmasses and ultimately to the formation of the present-day landscapes around the North-East Atlantic.

Yet the geodynamic processes responsible remain poorly understood. Here we summarize key aspects of these episodes, highlighting both similarities and differences in their effects in Greenland and Fennoscandia, which may shed light on the driving processes. We also speculate on likely mechanisms. We hope that these observations may provide constraints for testing future geodynamic models.

2. Interpretation strategy

Apatite fission-track data register only episodes of cooling from higher temperatures and contain no information on time spent at lower temperatures (Green et al., 2013). However, the presence of sedimentary remnants resting on basement defines times when the underlying basement was at the surface prior to a phase of burial and heating. Thus, integrating the apatite fission-track data with geological evidence can define multiple episodes of exhumation (cooling) and re-burial (heating). Similarly, peneplains document the end-result of an episode of uplift of the surface of the earth. Where the age for the final formation of a peneplain can be constrained by cover rocks, the presence of such erosion surfaces provides an important constraint on the history of

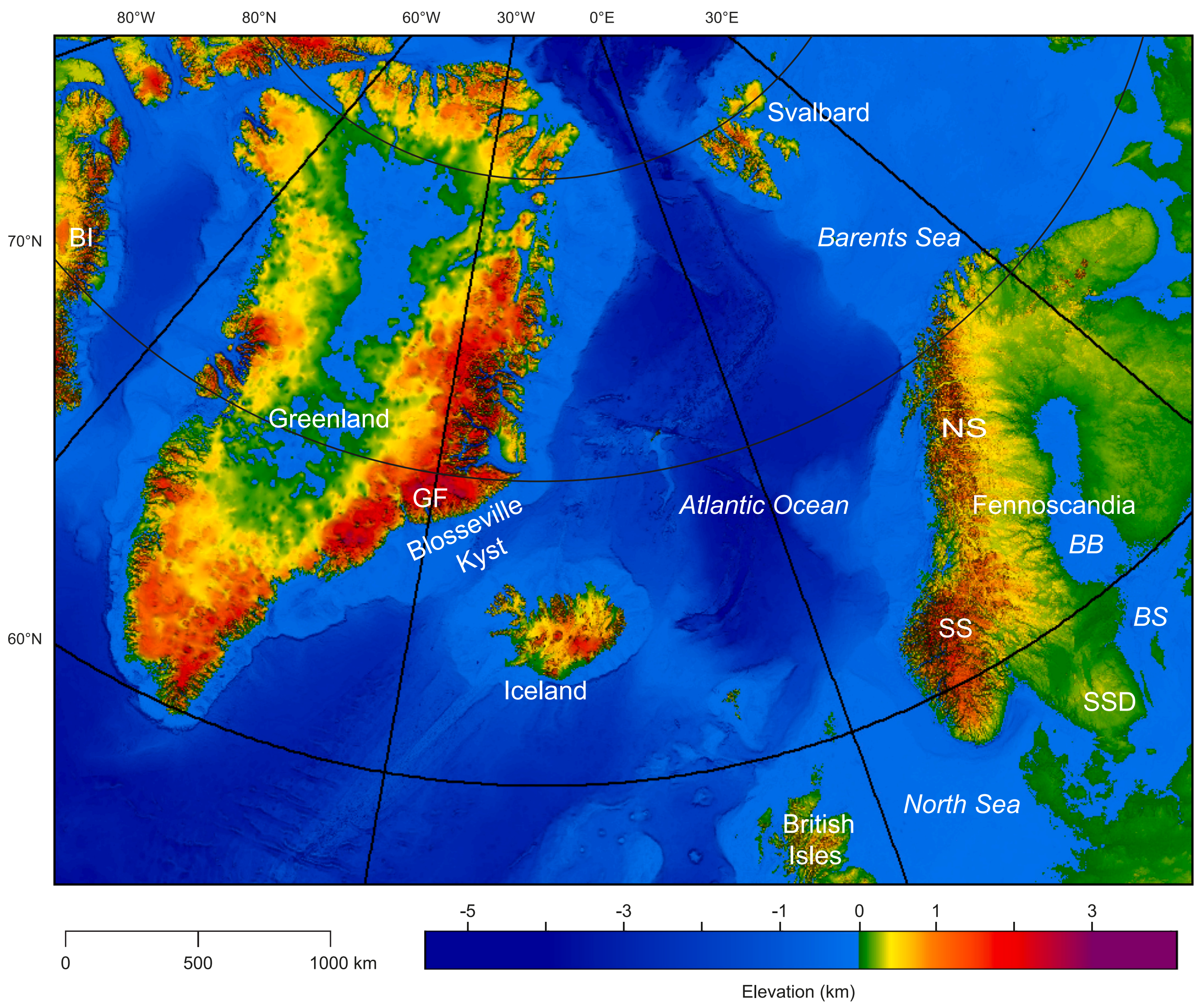

Fig. 1. Elevation of bedrock onshore and bathymetry offshore in the North-East Atlantic domain. Common features of the margins are that (a) one or several elevated plateaus dissected by deep valleys and that (b) deeply weathered, etch surfaces with hilly relief at relatively low elevations (Bonow et al., 2014). Note the much higher elevation in East Greenland compared to West Greenland. The load of the Greenland ice sheet causes a depression of up to 800 m in central Greenland whereas peripheral bulging caused by the ice load has a negligible effect on the elevation of Greenland's margins (Medvedev et al., 2013). Elevation data source: Amante and Eakins (2009). Modified after Bonow et al. (2014). BB: Bay of Bothnia. BI: Baffin Island. BS: Baltic Sea. GF: Gunbjørn Fjeld (3.7 km a.s.l.). NS: Northern Scandes. ScS: Scoresby Sund. SS: Southern Scandes (including the Miocene Hardangervidda peneplain). SSD: South Swedish Dome (including the Miocene South Småland Peneplain).

vertical movements in a region.

Here we adopt the definition that all surfaces graded to a base level are peneplains, irrespective of whether their detailed present-day form is hilly or flat (Green et al., 2013; Lidmar-Bergström et al., 2017). The formation of a peneplain involves erosion of rocks of different age and resistance by running water and slope processes during valley incision and valley-widening, whereas the final shape of the peneplain depends on the climatic conditions after its formation; e.g. weathering of the bedrock during warm and humid climates, resulting in a hilly relief with thick kaolinitic saprolites along fracture zones. Fluvial erosion to base level is fundamental for understanding the formation of extensive, low-relief surfaces. In the cases where the geological record documents that the sea transgressed a peneplain, base level was sea level. In the cases where a study area is known to have been near the sea at the time a peneplain formed (e.g. along passive continental margins), this is a reasonable hypothesis (Japsen et al., 2009).

Reconstruction of the thermal history based on AFTA data for one sample typically allows definition of three episodes of cooling (Green et al., 2013). However, we have been able to identify ten episodes of cooling (interpreted to reflect exhumation) across the study area because different episodes dominate in different regions and at different altitudes/depths. This results in a complex, spatial variation in paleotemperatures characterizing some episodes. For example, key paleothermal episodes show significant variation along an 800 km long N-S transect in Sweden without significant variation in elevation (Green et al., 2022b, fig. 15). Middle Jurassic cooling is recognized in the south and the north but is not recognized at central locations, where mid-Cretaceous cooling is defined. These variations are likely to be due to problems in resolving cooling episodes in samples affected by more than three episodes. Green et al. (2022b) argued that the key exhumation episodes affected Fennoscandia even in intermediate regions where they could not be resolved. This conclusion was reached because the differential vertical movements since Cambrian times must have been small along the east coast of Sweden (56–62^0 N), where the elevation of the Sub-Cambrian Peneplain only varies by a few hundred meters (Lidmar-Bergström et al., 2013).

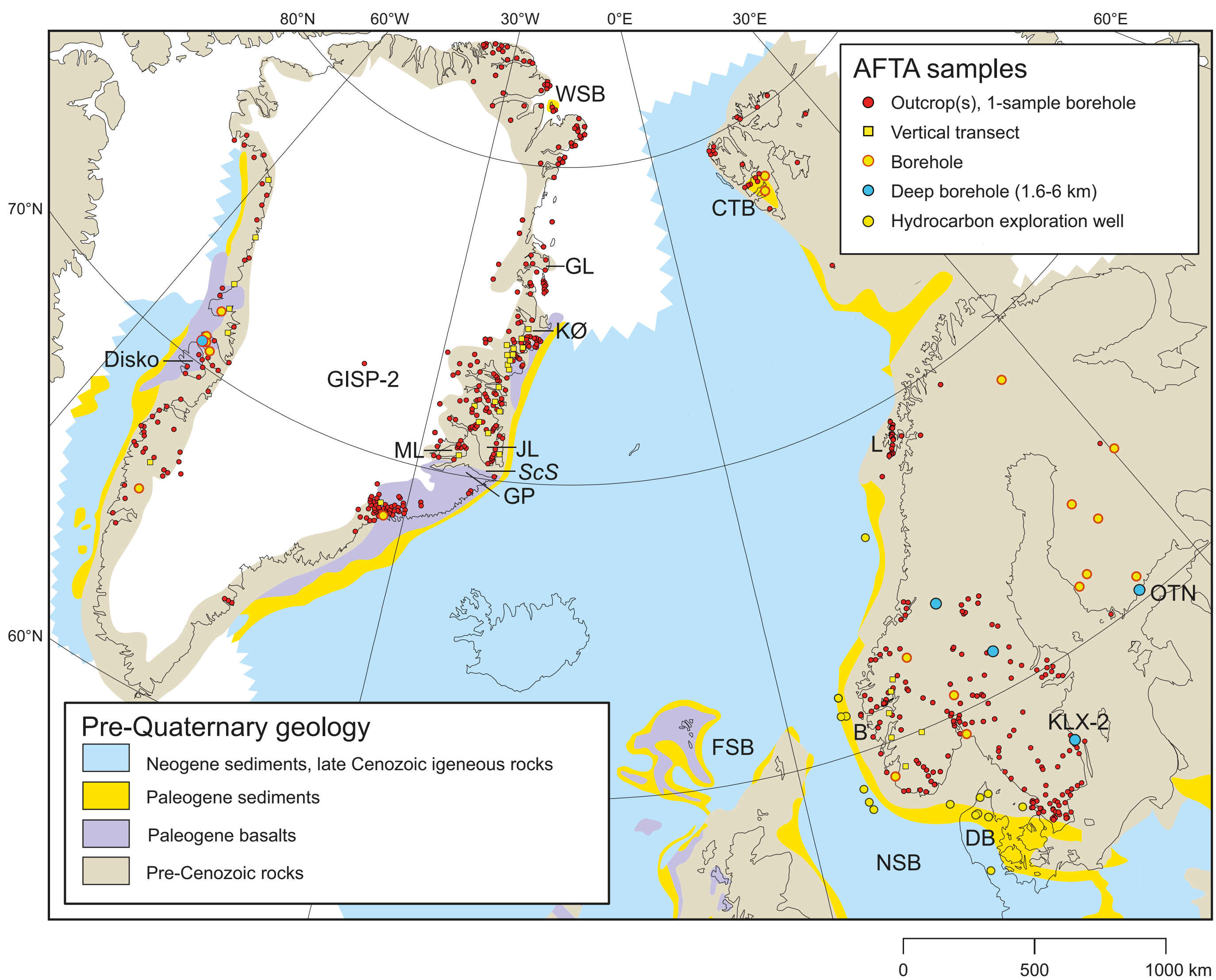

Fig. 2. Distribution of AFTA samples. Fennoscandia and the Danish Basin, 373 samples (Japsen et al., 2007; Green et al., 2022b). Greenland, 449 samples (Green and Japsen, 2018; Japsen et al., 2006, 2014, 2021a, 2023). Svalbard, 33 samples (Japsen et al., 2023). AFTA data and thermal history interpretation for the GISP-2 core in Supplemental Material. Annotated boreholes: GISP-2, KLX-2, OTN 1–3. Basemap slightly modified from Japsen and Chalmers (2000). B: Bergen. CTB: Central Tertiary Basin. DB: Danish Basin. FSB: Faroe-Shetland Basin. GL: Germania Land. GP: Geikie Plateau. JL: Jameson Land. KØ: Kuhn Ø. L: Lofoten. ML: Milne Land. NSB: North Sea Basin. WSB: Wandel Sea Basin. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. Onset of post-Caledonian episodes of regional exhumation (cooling) based on AFTA data and time intervals for peneplain formation. Intervening subsidence and burial not shown. Correlation with tectonic events indicated in the right-hand column; cf. the papers referred to in the caption to Fig. 2. Iceland Plume: Uplift along continental margins due to dynamic support by the Iceland Plume. Pangea break-up: Epeirogenic uplifts during break-up of Pangea. Plate reorganization: Uplift starting at the same time as plate reorganization. Plume dome: Doming above the Iceland Plume rising through the upper mantle. Plume impact: Onset of sea-floor spreading west of Greenland and inversion of fault zones during the onset of the Eurekan Orogeny. Vertical extent of the colored bands in the four left-hand columns indicate uncertainty for the onset of the exhumation episodes. The right-hand, colored column indicates the regional timing for the onset of exhumation in each episode based on data for the areas in the four columns. Timing of Maastrichtian domal uplift on Svalbard and of Paleocene inversion of fault zones in North Greenland from AFTA data adjusted by stratigraphic constraints from Canadian High Arctic (Embry et al., 2018). Stratigraphic landscape analysis based on Bonow et al. (2006b, 2014), Lidmar-Bergström et al. (2013), Japsen et al. (2018) and Bonow and Japsen (2021). Time intervals for peneplain formation defined by time between onset of exhumation and age of overlying sediments or onset of subsequent regional episode of exhumation. Timing of continental break-up from Oakey and Chalmers (2012), Gaina et al. (2017) and Dumais et al. (2021). FS: Fennoscandia. HV: Hardangervidda. LJP/MJP: Late/Mid- Jurassic Peneplain. LPS/UPS: Lower/ Upper Planation Surface. MCP: Mid-Cretaceous Peneplain. MTP: Mid-Triassic Peneplain. SPP: Sub-Permian Peneplain. SSP: South Småland Peneplain. STZ: Sorgenfrei-Tornquist Zone.

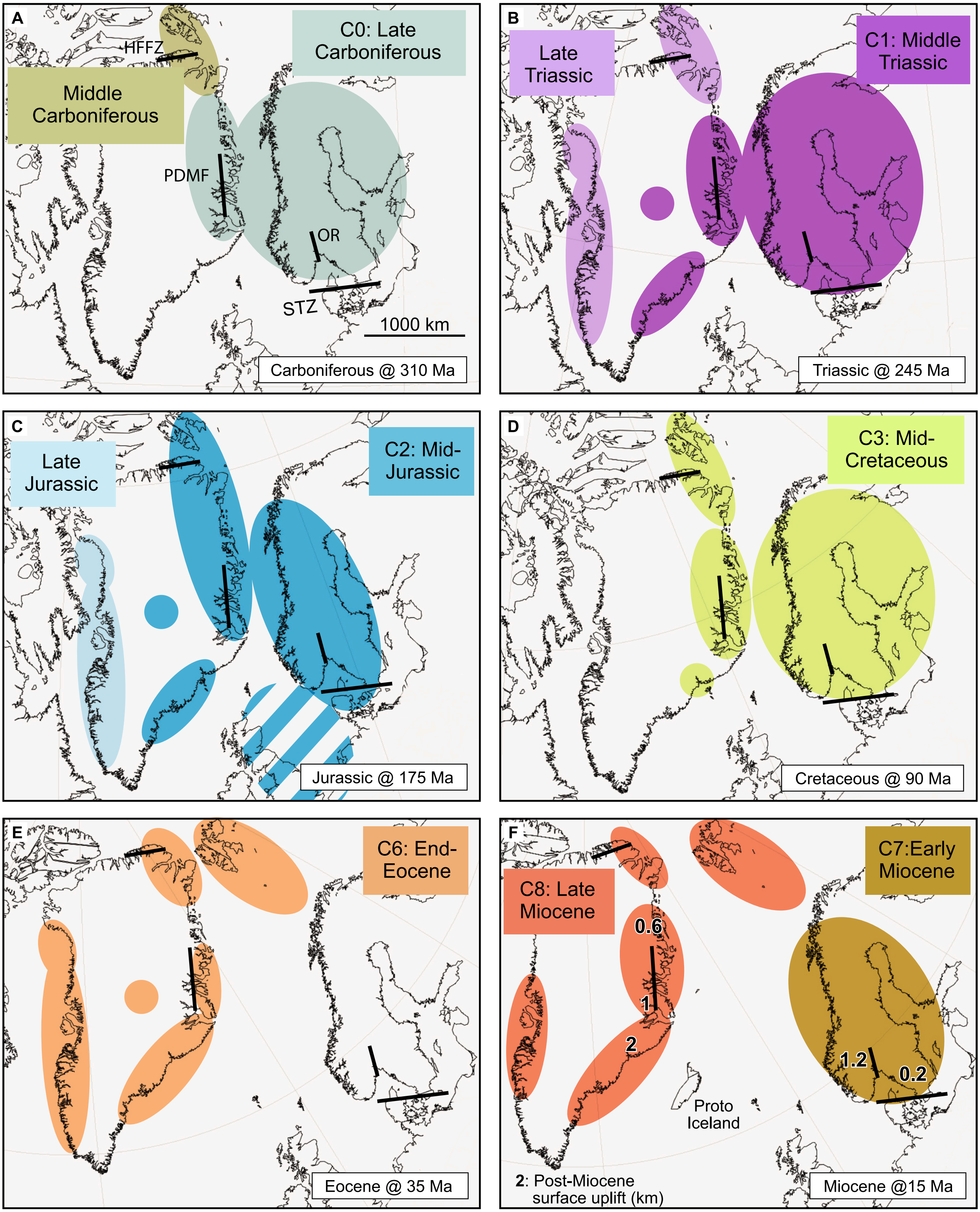

Fig. 4. Regions of broadly synchronous episodes of exhumation defined from AFTA data (Fig. 3). Subsidence of relatively minor basins during the episodes not indicated (e.g. subsidence of the Jameson Land Basin during the mid-Jurassic C2 episode). Location of present-day coastlines and plate configurations for the designated times (Matthews et al., 2016). Fig. C: Outline of the mid-Jurassic'Central North Sea Dome' indicated with hatched colour (Underhill and Partington, 1993). Fig. F: Post-Miocene surface uplift estimated from elevation of Miocene peneplains (Bonow and Japsen, 2021; Japsen et al., 2016, 2018). Black lines: faults. HFFZ: Harder Fjord Fault Zone. OR: Oslo Rift. PDMF: Post-Devonian Main Fault system. STZ: Sorgenfrei-Tornquist Zone.

3. Data

A consistent body of low-temperature thermochronology data and studies of the large-scale landscape development published over the last 20 years forms the backbone of this synthesis:

- Central West Greenland: Bonow (2005), Bonow et al. (2006a, 2006b), Japsen et al. (2005, 2006).
- North-East Greenland: Green and Japsen (2018), Bonow and Japsen (2021), Japsen et al. (2021a).
- Southern East Greenland: Bonow et al. (2014), Japsen et al. (2014).
- North Greenland, the Lomonosov Ridge (north of Greenland), Svalbard and the Barents Sea: Green and Duddy (2010), Knudsen et al. (2017), Japsen et al. (2021b, 2023).
- Fennoscandia: Bonow et al. (2003), Lidmar-Bergström et al. (2013), Japsen et al. (2010, 2016, 2018), Green et al. (2022b).
- Danish Basin: Japsen et al. (2007).

Furthermore, we include two reports as Supplementary Material:

- Geotrack Report GC891 which contains the unpublished thermal history based on AFTA for sample GC891–1 obtained from the central Greenland GISP-2 core (38^0 28′W, 72^0 35′N).
- Geotrack Report GC1066, previously unpublished, which includes thermal histories based on AFTA for 33 outcrop samples from northern West Greenland (72–76^0 N).

We base the following discussion on the interpretations presented in these sources, where AFTA data and a detailed analysis of all observations are provided. Throughout the text we refer to cases listed in the Appendix (included as Supplementary Material) where the paleothermal constraints for specific samples and geological observations allow us to estimate the thickness and age of missing sections.

Place names, sample locations and geological structures are indicated on the maps in Figs. 1, 2, 4.

4. Episodes of exhumation during break-up of Pangea

Episodic supercontinent assembly and break-up have a profound influence on the course of the Earth's geological, climatological, and biological evolution (Nance et al., 2014). Supercontinents become epeirogenically uplifted as heat accumulates beneath them, in particular because they shield the underlying mantle from subduction of old oceanic plates, resulting in heat accumulation that produces a concentration of plumes beneath the supercontinent (Worsley et al., 1984; Phillips and Bunge, 2007). Epeirogenic uplift will dominate tectonic activity during the lifespan of a supercontinent as trapped mantle heat accumulates beneath the largely stationary supercontinent, manifested as hot-spot activity, fragmentation and changes in global sea level (Nance et al., 2014; Nance, 2022). Dang et al. (2024) found that mantle plumes provided the dominant force that drove Pangea's break-up, particularly in triggering the initial break-up.

The mid-Carboniferous (c. 320 Ma) amalgamation of Gondwanaland and Laurussia and subsequent formation of the Variscan fold belt resulted in accumulation of heat beneath Pangea and thermal uplift that finally led to the first phase of extension and rifting of Pangea at c. 300 Ma (Veevers, 2004, 2013). The extension generated accommodation space for globally synchronous, cratonic sedimentary successions. Veevers (2004, 2013) presented a detailed account of the merger and break-up of Pangea based on stratigraphy and radiometric dating. Veevers defined two phases of extension of Pangea at c. 300 and 235 Ma followed by the incipient break-up by rifting of Atlantic margins by 190 Ma (anticipated by the c. 200 Ma Central Atlantic Magmatic Province, CAMP, in the middle of Pangea; Dang et al., 2024) and subsequent seafloor spreading that marked the end of Pangea as a single supercontinent.

Japsen et al. (2016) argued that late Carboniferous, Middle Triassic and Middle Jurassic episodes of exhumation defined by AFTA data across the southern Baltic Shield were the result of the main phases of epeirogenic uplift accompanying fragmentation of Pangea as identified by Veevers (2004, 2013). We discuss each of these episodes below.

4.1. *Late Carboniferous episode (C0)*

Late Carboniferous C0 exhumation affected North-East Greenland and Fennoscandia at about the same time, c. 310 Ma (Fig. 4A). Prior to this episode, thick sedimentary covers rested on basement, even in areas that today are considered to be stable cratons, such as Finland and southern Sweden where km-thick covers of Cambrian to Carboniferous sediments were present above the Sub-Cambrian Peneplain (Figs. 5B,C, 6A; entry C0a in the Appendix).

In North-East Greenland, the C0 episode correlates with the latest Carboniferous to mid-Permian unconformity, which separates the upper Permian, partly marine conglomerates of the Huledal Formation from the underlying, tilted and truncated latest Devonian to Carboniferous strata of the Traill Ø Group (Surlyk, 1990; Stemmerik, 2000). This unconformity marks the most profound change in tectonic style and overall depositional environment in the post-Caledonian development of East Greenland, representing the transition from a long period of crustal extension to a period of subsidence governed by thermal relaxation of the stretched and thinned crust (Surlyk, 1990). The unconformity corresponds to a sub-Permian peneplain covered by the sediments of the Huledal Formation (Haller, 1971; Larsen, 1988; Surlyk, 1990). Haller (1971, p. 320) summarized this change in the structural development, emphasizing that the Caledonian mountains had disappeared by the time this peneplain was developed: "When the upper Permian sea transgressed across the present outer fjord region most of the intra-Permian fault escarpments had been worn away. The late Paleozoic block mountain ranges had disappeared and given place to lowlands".

In Scandinavia, the C0 episode is represented by unconformities; e.g. in the late Carboniferous – Early Triassic Oslo Rift between an upper Carboniferous sedimentary succession (including marine strata) and underlying folded Cambro–Silurian rocks (Olaussen et al., 1994; Larsen et al., 2008). Permian sediments rest on Devonian in the Baltic Sea, and Devonian – lower Carboniferous rocks are absent in the Sorgenfrei-Tornquist Zone which defines the transition between the Baltic Shield and the Danish Basin (Fredén, 1994; Calner et al., 2013). Dykes of Carboniferous–Permian age across much of North-West Europe, including the Oslo Rift and southernmost Sweden, reflect the impact of the Skagerrak Plume centered south of Norway, c. 300 Ma (Torsvik et al., 2008). The plume impact thus post-dates the C0 episode by c. 10 Myr, suggesting that the onset of C0 exhumation in this region may reflect doming above the plume upon its arrival in the upper mantle (Campbell, 2007).

A sub-Permian unconformity in the North Sea to the west of Scandinavia (Glennie et al., 2003) marks a similar major change in tectonic style to that recognized in Greenland. There is also evidence of an important phase of exhumation towards the end of the Carboniferous, in the Southern Permian Basin of North-West Europe, represented by a pronounced base-Permian unconformity (Doornenbal and Stevenson, 2010).

Mid-Carboniferous exhumation in Svalbard and in the Carboniferous–Paleogene Wandel Sea Basin of North Greenland (beginning c. 325 Ma) correlates with a pronounced unconformity, reflecting Serpukhovian uplift of the northern margin of Pangea (Stemmerik and Worsley, 2005). It is possible that this episode represents an early phase of the late Carboniferous episode defined further south.

AFTA studies have also reported late Carboniferous exhumation across Ireland, Namibia, north-east Brazil and Angola (Green et al., 2000; Japsen et al., 2012a; Green and Machado, 2015). We thus consider the late Carboniferous phase of exhumation in North-East Greenland and Fennoscandia to be part of the first phase of break-up

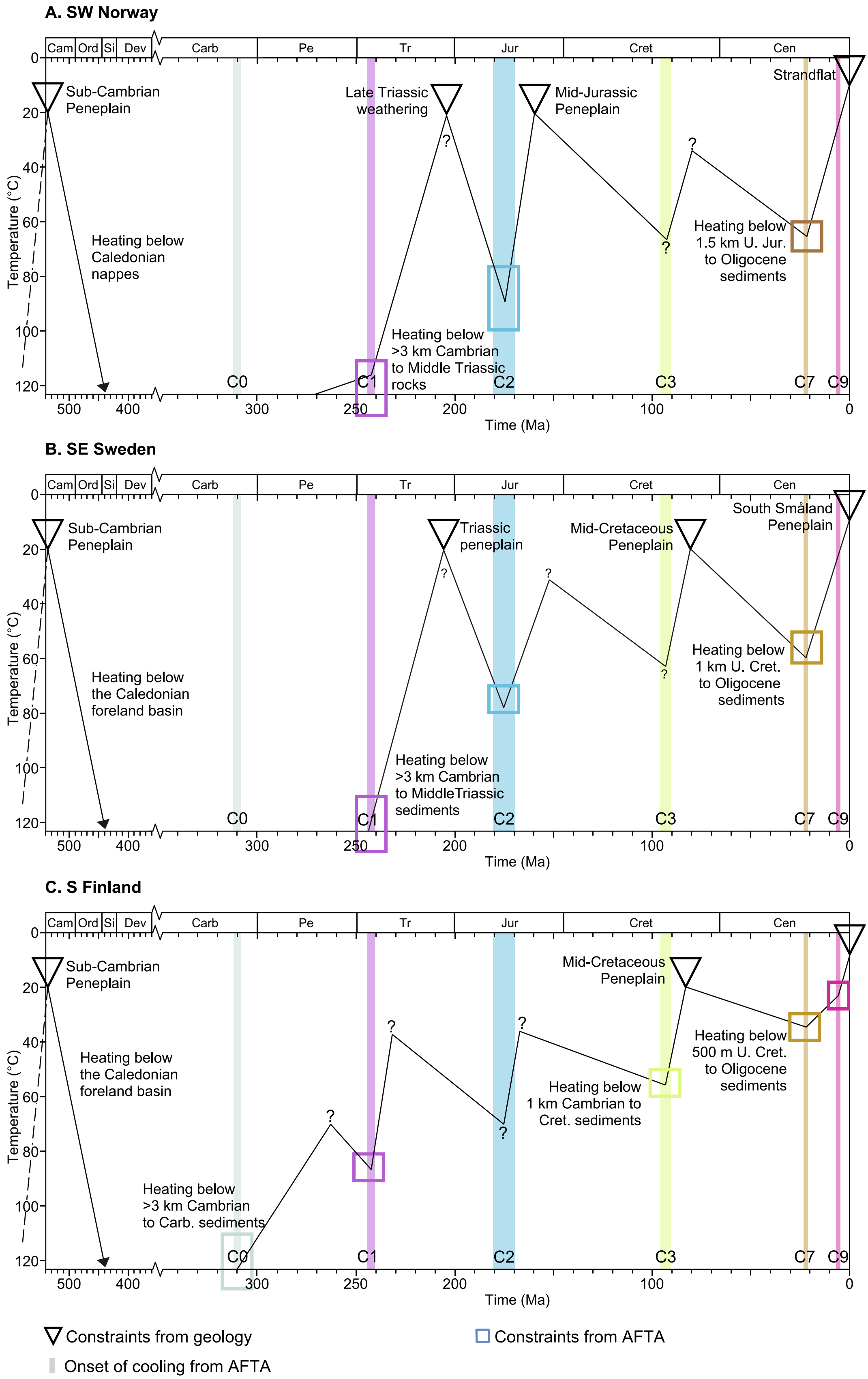

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Fig. 5. Heating and cooling (burial and exhumation) history of basement rocks in Fennoscandia now exposed at the surface. A: Coast of south-west Norway, near Bergen (60⁰N; Japsen et al., 2018; Green et al., 2022b). An Upper Jurassic outlier rest on the mid-Jurassic peneplain near the Pleistocene coastal plain ('strandflat'; Fossen et al., 1997; Fossen, 2023; Løseth, 2023). During the Caledonian Orogeny, rocks on the Sub-Cambrian Peneplain were heated to >300 °C below thick nappes (Fauconnier et al., 2014). B: Coast of south-east Sweden, near the KLX-2 borehole (57⁰N; Japsen et al., 2016; Green et al., 2022b). The Sub-Cambrian Peneplain, the mid-Cretaceous hilly relief, and the Miocene South Småland Peneplain are juxtaposed (Lidmar-Bergström et al., 2013; Japsen et al., 2016). Late Carboniferous C0 paleotemperatures for basement rocks below the Caledonian foreland basin (Gee et al., 2008) must have been higher than those for the OTN boreholes further east (Fig. C). Mid-Cretaceous C3 paleotemperatures cannot be resolved in this region where the separation between C2 and C7 values is minor, but the presence of Upper Cretaceous sediments defines the age of the mid-Cretaceous hilly peneplain.
C: Coast of southern Finland, OTN boreholes (60⁰N; Green et al., 2022b). The Sub-Cambrian Peneplain, which is defined along the coast, is truncated by the mid-Cretaceous hilly peneplain at low elevation at some distance from the coast (Lidmar-Bergström et al., 2013; Green et al., 2022b). A–C: The Sub-Cambrian Peneplain extended across Fennoscandia after its formation following exhumation that began c. 600 Ma (Lidmar-Bergström et al., 2013; Japsen et al., 2016). When the peneplain was fully developed prior to Cambrian transgression, rocks at this surface had cooled to a paleosurface temperature of c. 20 °C. The ranges of paleotemperatures are plotted as boxes with a height corresponding to the allowed range for the samples in question. The width of the boxes is fixed in centimeter. B–C: Paleotemperature constraints defined by sea-level intercept projections (SLIPs; Green et al., 2022b) for the boreholes in question. Carb: Carboniferous. Cret: Cretaceous. Jur: Jurassic. U: Upper. Details in the Appendix. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of Pangea.

4.2. Middle Triassic episode (C1)

Middle Triassic C1 exhumation began around the same time in East (and central) Greenland and Fennoscandia, beginning between 245 and 240 Ma (Figs. 4B, 7C). Prior to this episode, thick covers of upper Permian to Early Triassic sediments were present in the northern part of the Oslo Rift as well as significant columns of Paleozoic to Triassic sediments in West Greenland and southern Sweden (entries C1a in the Appendix). Uplift and erosion at this time led to the deposition of coarse-grained siliciclastic sediments across the wider region: the Middle Triassic Pingo Dal Group in North-East Greenland (Clemmensen, 1980; Oftedal et al., 2005), the Middle–Upper Triassic Skagerrak Formation (or Hegre Formation) around SW of Scandinavia (Bertelsen, 1980; Goldsmith et al., 2003; Jarsve et al., 2014).

In North-East Greenland, the C1 episode correspond to the major unconformity between the Pingo Dal Group and the underlying the Lower Triassic marine mudstones of the Wordie Creek Group (Bjerager et al., 2006). Extensive evidence of C1 cooling in the present-day basement areas west of the basins suggests that this event represents regional erosion of these areas, providing sedimentary input to the basins, indicative of C1 movements of the Post-Devonian Main Fault (PDMF) system, which includes the present-day, western boundary of the sedimentary basins (Vischer, 1943; Japsen et al., 2021a).

In Fennoscandia, the C1 episode is reflected in a major unconformity that separates upper Paleozoic from Mesozoic sequences in the southern, offshore continuation of the Oslo Rift (Ramberg et al., 2008). In southernmost Sweden, C1 exhumation corresponds to the unconformity below Upper Triassic sediments and in the removal of any trace of the superficial effusives which must have resulted from the late Paleozoic magmatic event (Bergström et al., 1982; Japsen et al., 2016). The resulting sub-Mesozoic denudation surface thus defines a mid-Triassic peneplain (Lidmar-Bergström, 1993).

A pronounced paleo-thermal offset is evident across the eastern margin of the Oslo Rift, where Middle Triassic C1 paleotemperatures for samples within and to the west of the Rift are consistently >110 °C, while values in samples to the east are <100 °C. These offsets define structurally controlled, differential exhumation (during Middle Triassic or later movements) because no significant variations in the paleogeothermal gradient are observed during this episode (Green et al., 2022b).

Triassic exhumation affected West and North Greenland and Svalbard 15–20 Myr later than the Triassic exhumation in other areas. In Svalbard and North Greenland this episode correlates with base-Carnian (~235 Ma) unconformities that mark drastic changes in the sedimentary environment (Dallmann, 2015; Bjerager et al., 2019; Japsen et al., 2021b). This time difference may indicate that the C1 episode affected East Greenland and Fennoscandia earlier than the areas to the west and north. Larsen et al. (2009) found that highly alkaline, volatile-rich melts, which formed in small volumes in the deep lithosphere, were indicative of incipient stretching in West Greenland during Late Triassic to Late Jurassic (c. 220–150 Ma), indicating delayed Triassic rifting in West Greenland compared to East Greenland (see subsequent Section).

AFTA studies have also reported Middle Triassic exhumation in Scotland and eastern Canada (Holford et al., 2010; Japsen et al., 2017). The recognition of the Triassic episode across a wide area of the northern hemisphere provides further evidence in support of the interpretation that this episode represents the second phase of break-up of Pangea. The relation between eruption of the 250–Ma Siberian Traps (Saunders et al., 2005) and the subsequent C1 episode is unclear.

4.3. Mid-Jurassic episode (C2)

Mid-Jurassic C2 exhumation began at broadly the same time in East (and central) Greenland and Scandinavia according to the AFTA data, beginning between 180 and 170 Ma, while not being recognized in Finland (Fig. 4C; possibly due to lack of resolution, Green et al., 2022a). Surlyk and Ineson (2003) showed that the main tectonic events and stratigraphic trends in East Greenland and the Danish Basin are highly similar, and that major regional uplift and erosion began at the Early–Middle Jurassic boundary (c. 175 Ma) in both areas. Subsequent subsidence began in the Aalenian (c. 172 Ma) in the North Sea and in the late Bajocian (c. 169 Ma) in East Greenland associated with the onset of rifting, resulting in major regional onlap and transgression. The duration of C2 exhumation was therefore only c. 5 Myr.

In North-East Greenland, extensive denudation of the present-day, interior basement terrains provided siliciclastic input to the Jurassic basins; e.g. the partly marine, Middle Jurassic sandstones of the Charcot Bugt and Pelion formations that overlie Triassic and upper Permian sediments or peneplained basement; e.g. the weathered, hilly peneplain on Milne Land where a km-thick rock column was removed during its formation (Figs. 8D, 9C2; entry C2a in the Appendix; Surlyk, 2003; Bonow et al., 2014). Lower Jurassic sediments are present in the Jameson Land Basin so, whereas this basin subsided, the areas to the west were uplifted, implying that the PDMF system west of Jameson Land was active during the C2 episode. AFTA data define Jurassic cooling beginning between 173 and 150 Ma in North Greenland and Svalbard. Evidence from the stratigraphic record indicates that this episode most likely also began at c. 175 Ma in this region (Dallmann, 2015; Japsen et al., 2021a).

In West Greenland, Late Jurassic exhumation (beginning between 160 and 150 Ma, about 20 Myr later than the C2 episode in East Greenland), led to stripping of the basement over large areas and to the formation of a deeply weathered, hilly peneplain (Bonow, 2005; Bonow et al., 2006a, 2006b; Japsen et al., 2006). The uplift and erosion coincided with increased extension evidenced by the intrusion of a 60 km long swarm of scattered alkaline dykes (c. 150 Ma; Larsen et al., 2009)

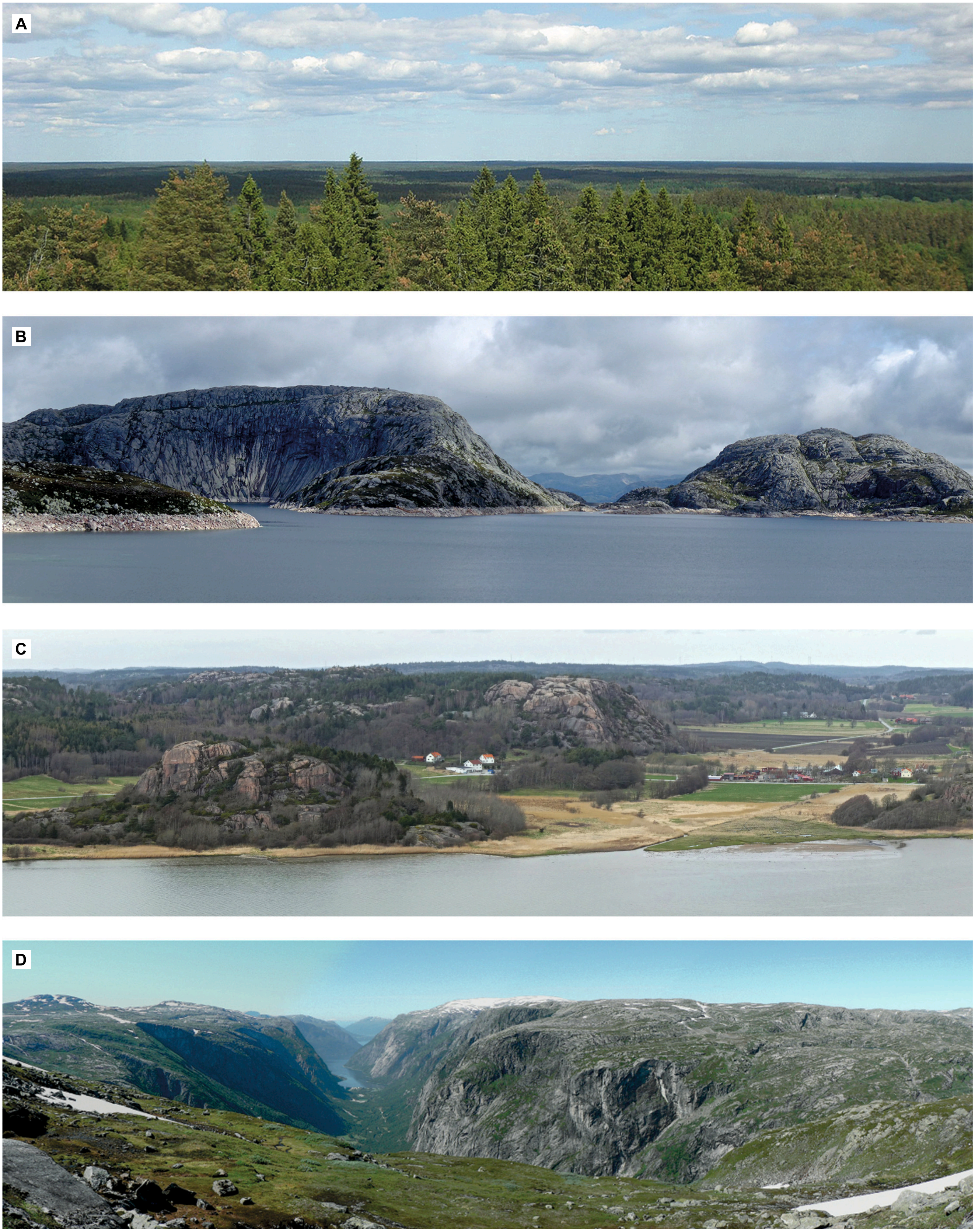

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Fig. 6. Peneplains in Fennoscandia. A: The Sub-Cambrian Peneplain (100 m a.s.l.; Lidmar-Bergström et al., 2013; Green et al., 2013, Fig. 9a). Photo from Aboda Klint (eastern Sweden, 59^{0}N), 30 km west of Paleozoic cover rocks. B: Exhumed remnants of Mesozoic hilly relief. The relief interpreted to represent a mid-Jurassic peneplain graded to base level during C2 exhumation (1000 m a.s.l.; Japsen et al., 2018, figure 4b1; Green et al., 2022b). Photo from an area south of Lysefjord (south-west Norway, 59^{0}N). Along much of the coast of western Norway, Jurassic sediments rest on basement, and three outliers of Jurassic sediments occur onshore and in the coastal zone (Bøe et al., 2010). The hilly relief has been modified by overriding ice, note the small cirque on the flank of the left-hand hill which rises 190 m above the lake in the foreground. C: Exhumed remnants of Mesozoic hilly relief. The relief interpreted to represent a mid-Cretaceous peneplain graded to base level during C3 exhumation (hill tops rise 100 m above the lake near sea level; Lidmar-Bergström et al., 2013; Green et al., 2022b). Photo from an area just east of Gerlesborg (southwestern Sweden, 58^{0}N). Outliers of Upper Cretaceous sediments rest on basement onshore southwestern Sweden, and a hilly basement relief occurs below the Cretaceous cover offshore west Sweden (Lidmar-Bergström, 1995; Lassen and Thybo, 2012). D: North-westernmost part of Hardangervidda. The vidda (plateau) represents a Miocene peneplain graded to base level during C7 exhumation (1200 m a.s.l.; Japsen et al., 2018, figure 4a1). Photo towards the west and Hardangerfjord (south-west Norway, 60^{0}N). This sub-horizontal peneplain truncates the tilted mid-Jurassic peneplain that defines the slopes of the Southern Scandes. The mid-Cretaceous C3 episode resulted in folding of the mid-Jurassic peneplain, and this denudation chronology thus defines the age of the Hardangervidda erosional surface as Cenozoic. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and two carbonatite complexes (165 and 158 Ma; Secher et al., 2009). The first evidence of rifting west of Greenland is dated at 135 Ma, much later than in East Greenland (Chalmers and Pulvertaft, 2001). It therefore seems likely that the Late Jurassic episode of exhumation in West Greenland reflects similar geological process as the C2 episode in East Greenland and Scandinavia, but with a considerable delay (Japsen et al., 2021a).

In Scandinavia, the geological record of the Danish Basin, the Sorgenfrei-Tornquist Zone and the area just north of the zone, contains evidence of a pronounced, mid-Jurassic phase of uplift and erosion (Norling and Bergström, 1987; Ziegler, 1990; Ahlberg et al., 2003; Nielsen, 2003). The uplift was preceded by volcanic activity along the Sorgenfrei-Tornquist Zone in Sweden (177 Ma), where large variations in the lithosphere thickness may have caused transient, small-scale mantle convection (Tappe et al., 2016).

C2 exhumation also led to the formation of a mid-Jurassic peneplain in Scandinavia, graded to the base level of the adjacent ocean, and AFTA data document removal of a km-thick rock column during the formation of the peneplain (entry C2b in the Appendix). In the Norwegian offshore, a deeply weathered, hilly peneplain is preserved below a cover of Middle-Upper Jurassic and younger sediments (Riis, 1996; Japsen et al., 2018, Fig. 2). Today this peneplain is exposed onshore along the flanks of the Southern Scandes from sea-level (where an outlier of marine Oxfordian sediments constraints the age of the surface) to about 1 km altitude (where it is truncated by the Miocene peneplain of Hardangervidda) (Fig. 6B,D, Section 6.2; Fossen et al., 1997; Lidmar-Bergström et al., 2013; Japsen et al., 2018). The Scandes are the mountains along the Atlantic margin of Scandinavia (Fig. 1). A mid-Jurassic peneplain is also documented offshore and onshore the Lofoten archipelago, where Middle Jurassic sediments overlie deeply weathered basement on the island of Andøya (68–69^0 N; Dalland, 1980; Løseth and Tveten, 1996).

The mid-Jurassic' Central North Sea Dome' is a regional, domal uplift that resulted from the impingement of a broad-based, transient plume head at the base of the lithosphere (Underhill and Partington, 1993; Quirie et al., 2019). Doming began in the late Toarcian (c. 175 Ma) and was thus part of the C2 episode, reaching its maximum areal extent in the Aalenian (c. 172 Ma) prior to deflation of the dome and subsequent Bajocian–Callovian volcanism (onset c. 170 Ma) and early Kimmeridgian rifting (c. 155 Ma). The duration of the domal uplift as well as the time lag between the onset of doming and the volcanism associated with the plume impact at the base of the lithosphere are thus about 5 Myr. This provides support for the notion that the onset of C2 exhumation in this region reflects doming above a plume upon its arrival in the upper mantle (Campbell, 2007).

The results from AFTA and the extent of the deeply weathered, hilly peneplains of Jurassic age exposed along the coasts of West and North-East Greenland and Norway show that Jurassic exhumation affected a much wider area than the region mapped in the North Sea, extending at least 2000 km north-south and 1000 km east-west (Fig. 4C).

AFTA studies also record mid-Jurassic exhumation in northern Australia, north-west Canada, Angola, South Africa and north-east Brazil (Duddy et al., 2004; Green et al., 2017; Japsen et al., 2012a; Green and Machado, 2015). Several studies identified plumes related to the Karoo Large Igneous Province (c. 183 Ma) as the primarily factor that drove the break-up between Africa and Antarctica (Storey, 1995; Dang et al., 2024). These observations indicate that the C2 episode was part of a global phenomenon – the third phase of the fragmentation of Pangea.

5. Episodes of exhumation after break-up of Pangea and before the opening of the North-East Atlantic

5.1. Mid-Cretaceous episode (C3)

Mid-Cretaceous C3 exhumation (beginning between 95 and 90 Ma) affected wide areas in East and North Greenland, Svalbard and Fennoscandia and coincides with the inversion of the Sorgenfrei-Tornquist Zone (Fig. 4D; Japsen et al., 2007, 2016). Prior to the exhumation, thick sedimentary covers were present above the Sub-Cambrian Peneplain in southern Finland (Fig. 5C) and above the mid-Jurassic peneplains on Germania Land (North-East Greenland; Fig. 7B) and in Lofoten (entries C3a in the Appendix).

In North-East Greenland, C3 exhumation led to removal of much of the post-rift succession that had accumulated above the rift and its margins in the interior of North-East Greenland after the rift climax at the Jurassic–Cretaceous transition (Japsen et al., 2021a). Onshore North-East Greenland, the episode corresponds to the mid-Turonian, erosional unconformity at the base of the upper Turonian – lower Maastrichtian Jackson Ø Group, recording a phase of basin reorganization (Bjerager et al., 2020). Offshore North-East Greenland a mid-Cretaceous tectonic reorganization occurred sometime between the late Albian and the middle Santonian (Fyhn et al., 2021).

On Lofoten – the conjugate margin to North-East Greenland – differences in C3 paleotemperatures over short distances suggest differential exhumation across discrete structures (Green et al., 2022b). Offshore Lofoten, a regional mid-Cenomanian unconformity (c. 95 Ma) in extensional basins (Henstra et al., 2016), correlates with C3 episode.

The C3 episode resulted in the formation of a deeply weathered, mid-Cretaceous peneplain over large parts of Sweden and Finland (Fig. 6C; Lidmar-Bergström et al., 2013; Green et al., 2022b). In southernmost Sweden, Campanian sediments and widespread occurrences of flint erratics derived from a former cover of Upper Cretaceous chalk occur on the mid-Cretaceous hilly peneplain with kaolinized basement rocks (Lidmar-Bergström, 1995).

The mid-Cretaceous episode also resulted in tilting of the mid-Jurassic peneplains in North-East Greenland and Norway as demonstrated by the variation of paleotemperatures across the Southern Scandes (Fig. 9 C3; Green et al., 2022b, fig. 13). Paleotemperatures in all three Mesozoic episodes (C1-C3) at any elevation are much higher in the central part of these mountains, and they are all offset by roughly similar amounts compared to locations to the north and south, whereas Miocene C7 values show only minor differences. The higher values in the three Mesozoic episodes in the central region are best explained by a larger amount of vertical displacement during the mid-Cretaceous episode. Furthermore, in the Baltic Sea (56^{0}N), Upper Cretaceous chalk rests

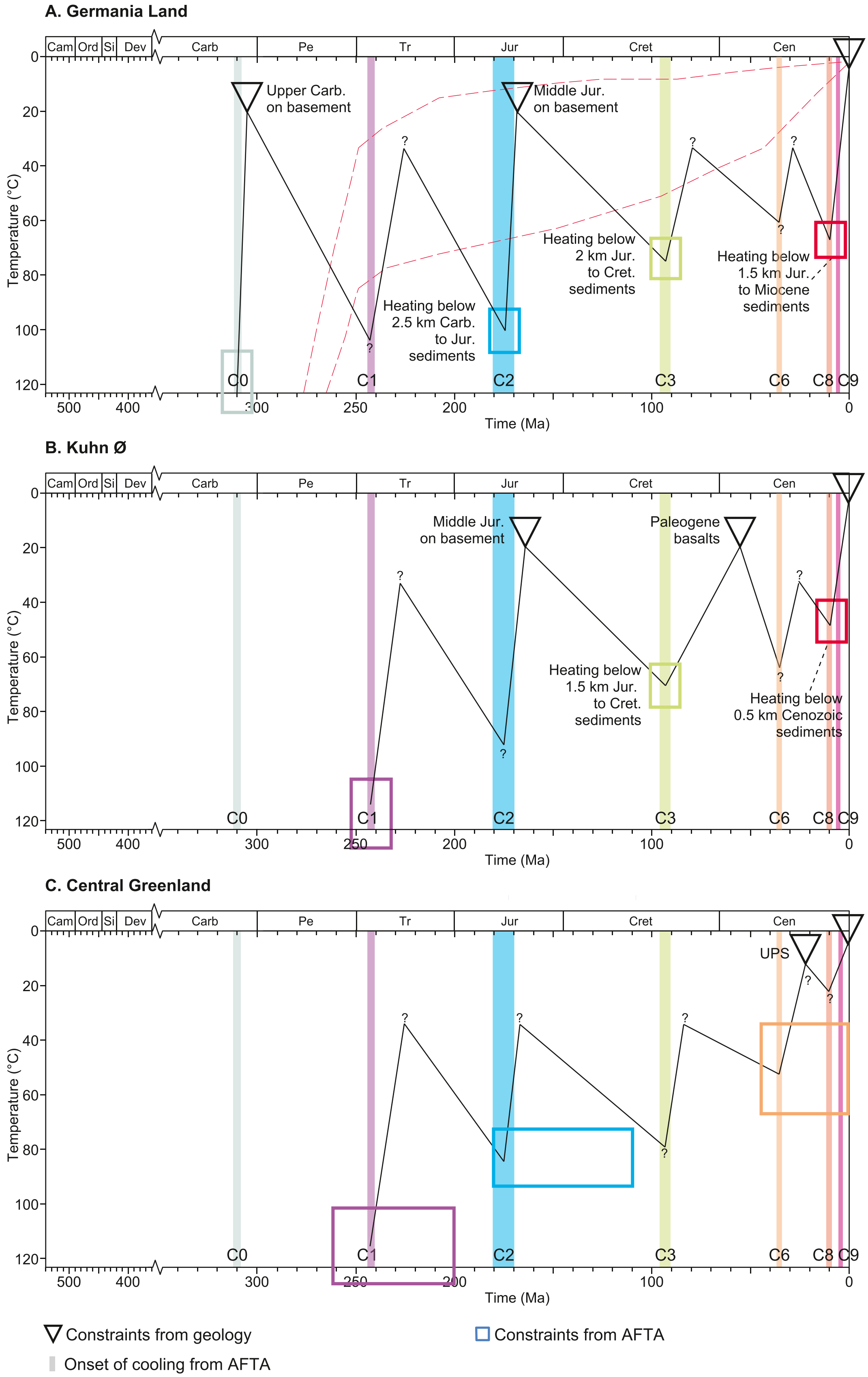

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Fig. 7. Heating and cooling (burial and exhumation) history of basement rocks in Greenland now exposed at the surface / buried below the Greenland Ice Sheet. A: Germania Land at sea level, North-East Greenland (77^{0}N; Japsen et al., 2021a; Green et al., 2022b), where Upper Carboniferous and Middle Jurassic sediments rest on basement (Bojesen-Koefoed et al., 2012; Piasecki et al., 1994). Red dashed lines: Thermal history reported by Pedersen et al. (2012). B: Kuhn Ø summits, North-East Greenland (75^{0}N; 1.2 km a.s.l.; Japsen et al., 2021a). Kuhn Ø is a tilted Late Jurassic – Early Cretaceous fault block where Middle Jurassic sediments onlap basement on the western side of the island and Palaeogene basalts are present in the summits (Surlyk, 2003). C: Central Greenland, GISP-2 core (73^{0}N; 146 m a.s.l., below 3 km of ice; Henriksen et al., 2009). A and B: The ranges of paleotemperatures are plotted as boxes with a height corresponding to the allowed range for the samples in question. The width of the boxes is fixed in centimeter. C: Boxes showing the ranges of paleotemperatures and constraints on the onset of cooling according to the thermal history interpretation. Abbreviations in Fig. 5. Details in the Appendix. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

unconformably on Paleozoic strata that are progressively truncated towards the coast of Sweden (Sigmond, 2002). We suggest that final folding of these strata occurred during the C3 episode.

The C3 episode is coeval with the onset of inversion of the Sole Pit Axis in the southern North Sea and with a regional Turonian unconformity in the Faroe–Shetland Basin (Stoker and Ziska, 2011; Green et al., 2018). Regional exhumation across Fennoscandia between the zones of compression in the Sorgenfrei-Tornquist Zone in the south and extension in Lofoten in the north suggests that the C3 episode may have been caused by intra-plate stresses.

A Late Cretaceous event of intraplate basin inversion and basement thrusting in central Europe occurred after a plate-tectonic reorganization that resulted in changes in the relative motion between the European and African plates at *c*. 90 Ma (Kley and Voigt, 2008). These events may be related to a global-scale, mid-Cretaceous phase of plate reorganization around 100 Ma (Müller et al., 2016), which also suggests a link to transmission of intra-plate stresses.

5.2. Maastrichtian and Paleocene episodes (C4, C5)

Maastrichtian C4 exhumation (beginning between 72 and 65 Ma) is documented by AFTA and apatite fission-track data from the Canadian High Arctic (north of 68^{0}N), the Lomonosov Ridge (near the North Pole), Svalbard and parts of the Barents Sea (Arne et al., 1998, 2002; Green and Duddy, 2010; Knudsen et al., 2017; Vamvaka et al., 2019; Japsen et al., 2023). The exhumation is reflected in a latest Cretaceous unconformity across the North American Arctic and the Barents Shelf (Ricketts, 1994), that Embry et al. (2018) dated as late Maastrichtian (68 Ma), and we adopt this value as the best indication of the onset of this episode. A Maastrichtian unconformity is an important marker both onshore and offshore West and North-East Greenland (Japsen et al., 2005, 2023; Bjerager et al., 2020; Fyhn et al., 2021). On Svalbard, Maastrichtian exhumation led to the formation of the Albian – mid-Paleocene hiatus below the Central Tertiary Basin that involved the removal of several kilometers of Cretaceous sediments (entry C4a in the Appendix). Japsen et al. (2023, figure 11a) provides a map of the areas affected by late Maastrichtian uplift and subsidence around the North-East Atlantic.

Japsen et al. (2023) suggested that the Maastrichtian uplift reflects doming above the rising Iceland Plume upon its arrival in the upper mantle, prior to its impact at the base of the lithosphere at 62 Ma (the onset of eruption of picritic lavas in West Greenland; Pedersen et al., 2017). The lag time is thus about 6 Myr between the onset of pre-impact doming and the impact itself, in agreement with the observation that indicate that such lag times are 3–10 Myr (Campbell, 2007). The regional extent of the Maastrichtian unconformity is also in agreement with observations indicating that the diameter of such domes is of the order of 1000 to 2000 km. The hypothesis is consistent with the placing of the rising plume head under central northern Greenland (Celli et al., 2021).

The mid-Paleocene impact of the plume at the base of lithosphere under Greenland caused volcanism, large-scale subsidence and outward flow from the plume head, contributing to the onset of sea-floor spreading west of Greenland (Gill et al., 1992; Chalmers and Laursen, 1995; Harrison et al., 1999). The movement of Greenland led to the mid-Paleocene onset of the Eurekan Orogeny that affected wide areas across the Canadian High Arctic, North Greenland and Svalbard involving inversion of fault zones, thrusting and formation of foreland basins (Thorsteinsson and Tozer, 1970; Håkansson and Pedersen, 1982, 2015; Ricketts, 1994; Oakey and Chalmers, 2012; Dallmann, 2015; Piepjohn et al., 2016; Jones et al., 2017). The SSW-NNE movement of Greenland during the Paleocene stage of the Eurekan Orogeny led to the formation of the West Spitsbergen Fold Belt on Svalbard by initial SSW-NNE compression followed by minor transpressional modifications and to the onset of subsidence of the Central Tertiary Basin as a foreland basin (Manby and Lyberis, 1996; Bergh et al., 1997; Oakey and Chalmers, 2012; Jones et al., 2017; Japsen et al., 2021b, 2023).

Localized, mid-Paleocene C5 exhumation (beginning c. 60 Ma) of inverted fault zones is documented by low-temperature thermochronology data in the eastern Canadian Arctic and in the Wandel Sea Basin (entry C5a in the Appendix; Arne et al., 2002; Vamvaka et al., 2019; Japsen et al., 2023). Embry et al. (2018) dated the corresponding unconformity in the Canadian High Arctic as Danian (62 Ma), and we adopt this value as the best indication of the onset of this episode. For example, heavily deformed Upper Cretaceous sediments and older rocks occur within the inverted fault zones of the Wandel Sea Basin, in contrast to the widespread distribution of the upper Paleocene – middle Eocene Thyra Ø Formation (Håkansson and Pedersen, 1982; Svennevig et al., 2016). Japsen et al. (2023, figure 11b) provide a map of the areas affected by mid-Paleocene uplift and subsidence around the North-East Atlantic.

Maastrichtian–Paleocene exhumation (beginning between 72 and 61 Ma), is recognized locally in Norway along the Møre-Trøndelag Fault Zone (62^{0}N; Gabrielsen et al., 2018). This episode correlates with a major input of Paleocene sediment offshore, interpreted to indicate major uplift and erosion of the onshore margin (Sømme et al., 2019). Coeval tectonic activity further north (63–64^0 N) resulted in the Danian, Ormen Lange turbidite system with reworked Cretaceous, Jurassic and Triassic sediments reflecting tectonic activity and presence of Mesozoic cover units in the provenance area (Gjelberg et al., 2005). Sømme et al. (2019) suggested that the Paleocene uplift of western Norway was driven by the arrival of the Iceland plume.

6. Episodes of exhumation after break-up in the North-East Atlantic

6.1. End-Eocene episode (C6)

End-Eocene C6 exhumation (beginning c. 35 Ma) interrupted the Eocene regime of subsidence and burial across Greenland (including central Greenland), the Canadian High Arctic, Svalbard and the Barents Sea (Fig. 4E; Green and Duddy, 2010; Embry and Beauchamp, 2019; Japsen et al., 2023). AFTA data from Fennoscandia do not resolve cooling related to the C6 episode, but an end-Eocene unconformity offshore North-West Europe reflects a dramatic change in the basin configuration (Stoker et al., 2005). Note that at no locations do AFTA data record evidence of exhumation at the time of break-up in the North-East Atlantic in the earliest Eocene, but sporadic occurrences of cooling at c. 55 ma in East and West Greenland is associated with the widespread Eocene intrusive activity across the region (Larsen et al., 2014; Japsen et al., 2021a; Green et al., 2022b).

C6 exhumation removed sedimentary successions c. 2 km thick from wide areas across the Wandel Sea Basin, East Greenland and around the

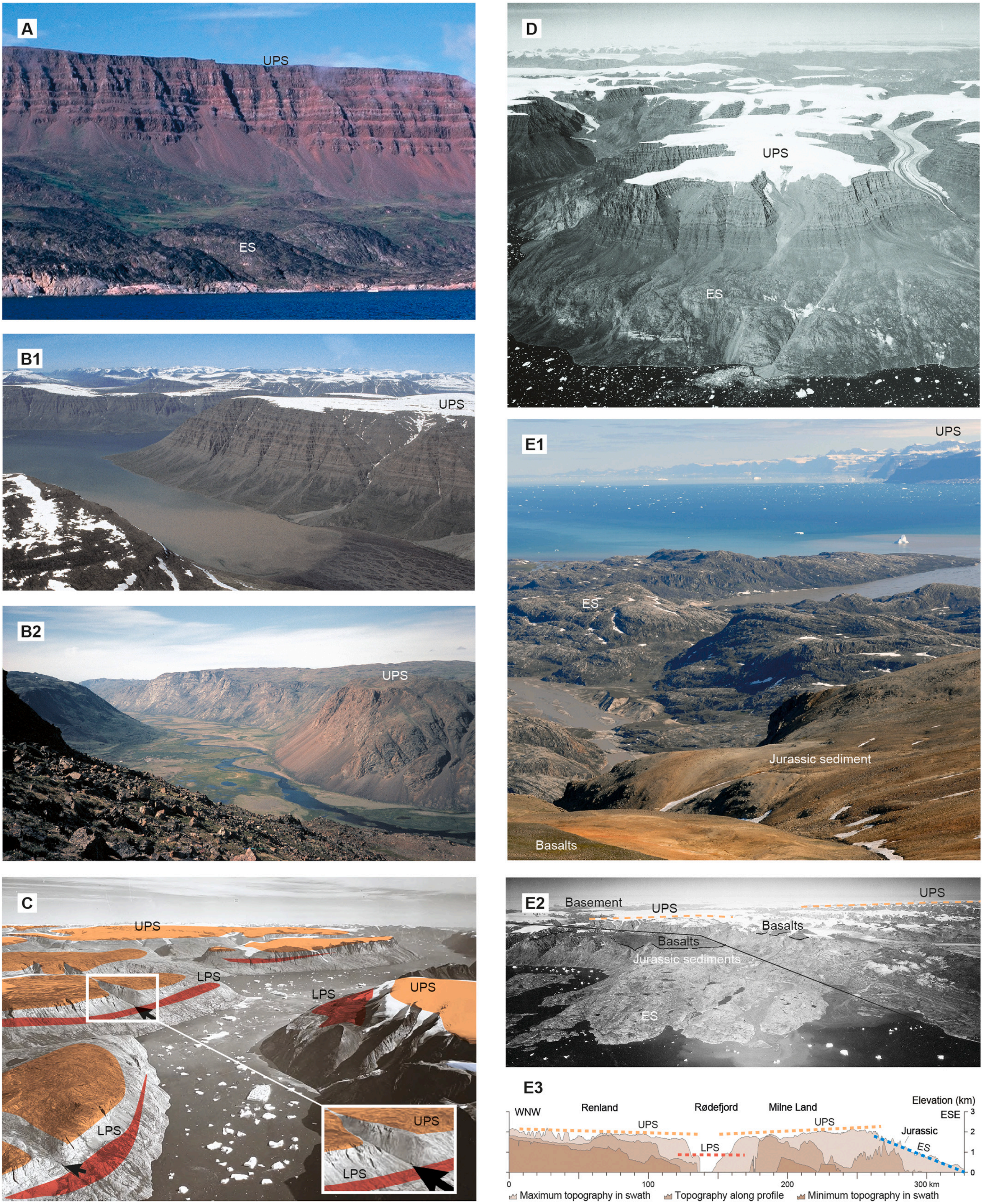

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Fig. 8. Peneplains in Greenland. A: Exhumed basement hills, part of a deeply weathered, Mesozoic etch surface (ES), beneath high cliffs of Paleocene basalts (summit level at 900 m a.s.l. defined by the Upper Planation Surface, UPS; see Figs. B1, B2) (Bonow, 2005). The etch surface represents a Late Jurassic peneplain graded to base level during a late phase of C2 exhumation (Japsen et al., 2006). Note that elsewhere in this sedimentary basin (the Nuussuaq Basin), Albian sediments rest on basement (Dam et al., 2009). Photo from Fortunebay (southern Disko, West Greenland, 69^{0}N). B1 and B2: The UPS in central West Greenland. The UPS represents a Cenozoic peneplain graded to base level during C6 exhumation (900 m a.s.l.; Japsen et al., 2006, Fig. 4). Photos from Kangerluk (southern Disko, 69^{0}N, B1) and Sarfartoq (120 km SE of Sisimiut, 66^{0}N, B2). The UPS cuts across Precambrian basement (B2), and as the peneplain can be traced northwards, where it cuts across Paleocene basalt on Disko (B1), this denudation chronology defines the age of the UPS as Cenozoic. Photo B1: Niels Nielsen, photo B2: Karsten Secher. C: Incision of the Lower Planation Surface LPS below the UPS as valley benches (Bonow and Japsen, 2021, fig. 20). The UPS (orange) and the LPS (red) are 1800 and 1000 m a.s.l., respectively. Photo from Nordvestfjord looking east towards Flyverfjord (East Greenland, 72°N). The LPS represents a post-Miocene peneplain graded to base level during C9 exhumation. Note the V-shaped valleys (black arrows) that demonstrate that rivers, not glaciers, dominated the landscape during the formation of the LPS in the late Miocene. D: The UPS developed across Eocene basalts and basement rocks (in the background). The UPS is thus a post-basalt erosion surface, interpreted to represent a peneplain graded to base level during C6 exhumation (1800 m a.s.l., Bonow and Japsen, 2021, fig. 12b). Photo from Gåseland (East Greenland, 71°N). E1 to E3: Relationship between the deeply weathered, hilly basement surface (etch surface, ES) and the UPS on southern Milne Land (East Greenland, 71^{0}N; Bonow and Japsen, 2021, fig. 11). Middle Jurassic Charcot Bugt Formation and Paleogene basalts rest on the ES which together with AFTA data defines its age as mid-Jurassic, graded to base level during C2 exhumation. Also here, the UPS truncates basement and Eocene basalts, and it is interpreted to be the result of C6 exhumation. E1: View from southern Milne Land towards south-east across Scoresby Sund towards the Geikie Plateau (1700 m a.s.l.) where the UPS cuts across Eocene basalts. The tilted ES is characterized by distinct hills defined by intensively weathered fracture systems. E2: View towards north-west of the tilted ES on southern Milne Land. The extensive UPS is developed across Milne Land and beyond. Black line: Approximate location between the 210 and 340 km marks of the profile in D3. E3: Swath profile along the black line in E2 illustrating the relationship between three surfaces: ES, UPS and the LPS. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Central Tertiary Basin on Svalbard, and in several places, the removed section consisted of Eocene sediments (entry C6a in the Appendix). In North and North-East Greenland, the episode involved reverse fault movements caused by compression (Upton et al., 1980; Piepjohn and von Gosen, 2001; Guarnieri, 2015; Japsen et al., 2021b, 2023). Renewed magmatic activity in East Greenland towards the end of the Eocene (Larsen et al., 2014) emphasizes the tectonic origin of the C6 episode. Offshore North-East and South-East Greenland, a significant phase of progradation occurred at the Eocene–Oligocene transition (Larsen et al., 1994; Petersen, 2021; Fyhn, 2024). Oligocene sediments are absent on the shelf off central West Greenland, and the hiatus corresponds to a low-angle unconformity on seismic sections (Gregersen et al., 2022).

As a result of C6 exhumation, a peneplain was graded to the level of the adjacent ocean along the margins of both West and East Greenland; the Upper Planation Surface, UPS, which cuts across Paleogene basalts and older rocks in both regions (Figs. 8A,B,D, 9C6; see review by Bonow and Japsen, 2021).

C6 denudation began around the time when sea-floor spreading west of Greenland had ended and thus post-dates the Eurekan Orogeny (Srivastava, 1978; Tessensohn and Piepjohn, 2000; Oakey and Chalmers, 2012). The onset of the episode also coincided with a minimum rate of sea-floor spreading and a significant change in the spreading directions in the North-East Atlantic. Adjustments along the eastern and southern boundary of the European Plate may have caused this change (Gaina et al., 2017), indicating substantial changes in the stress regime in and around the North-East Atlantic. Dewey et al. (1989) also identified a major change in tectonic phases at the Eocene–Oligocene transition in the western Mediterranean from a model based on a study of Atlantic fracture zones to integrate the motion of Africa relative to Europe. These changes at the southern margin of Europe may have generated forces transmitted across the spreading center north-west of Europe, through the asthenosphere (Höink et al., 2012; Colli et al., 2018).

6.2. Early Miocene episode (C7)

Early Miocene C7 exhumation (beginning between 23 and 21 Ma) affected a wide region across Norway and Sweden and has also been identified in Finland from analysis of deeper samples from the 6-km deep OTN boreholes (Fig. 4F). AFTA, VR and sonic data in wells offshore south and southwest of Norway – including the Sorgenfrei-Tornquist Zone – also provide evidence for early Miocene exhumation, with 600–1000 m of section removed (Japsen et al., 2007, 2010). A regional base-Miocene unconformity in the offshore sedimentary basins of North-West Europe emphasizes the vast regional extent of this episode (Stoker et al., 2005; Dybkjær et al., 2020). We therefore suggest that evidence of Neogene exhumation along the Norwegian margin reported in a number of studies without precise timing constraints most likely represents C7 exhumation (Hansen, 1996; Japsen, 1998; Baig et al., 2019; Phillips et al., 2020).

Prior to C7 exhumation, AFTA and VR data from Jurassic sediments and basement show that >1 km of Jurassic–Oligocene sediments had accumulated above the mid-Jurassic peneplain along the Norwegian west coast, and AFTA data show that about 500 m of Upper Cretaceous to Oligocene sediments had accumulated above the mid-Cretaceous peneplain in southern Finland (Figs. 5A,C; entries C7a in the Appendix). In contrast, C7 paleotemperature profiles from the central part of Southern Scandes project to an intercept close to 20 °C at the level of the highest summits at c. 2.5 km asl, suggesting that this level was close to the surface when early Miocene exhumation began (entry C7b in the Appendix).

Prior to the Miocene, sea covered all of what is now Denmark for millions of years, but in the early Miocene, the sea became filled with deltaic sediments transported by braided rivers originating in the uplifting Scandinavian hinterland (Rasmussen et al., 2010; Olivarius et al., 2014). The braided river systems from Norway and Sweden reached Denmark at c. 22 Ma, followed by deltas that prograded towards the SSW (Rasmussen, 2014). The rivers transported conglomerates with flint and quartzite clasts up to 5 cm, which are the most coarse-grained deposits in the Danish pre-Quaternary succession (Rasmussen and Dybkjær, 2020).

C7 exhumation resulted in formation of a peneplain graded to sea level during the Miocene, represented by the plateau surfaces of Hardangervidda (Figs. 6D, 9C7; Southern Scandes), the South Småland Peneplain (Fig. 1; the South Swedish Dome) and the base-Miocene unconformity offshore Norway (Lidmar-Bergström et al., 2013; Japsen et al., 2016, 2018, Fig. 2).

Neogene uplift began in the early Miocene within and north of the Sorgenfrei-Tornquist Zone, whereas Miocene sediments accumulated in the Danish Basin to the south (Rasmussen et al., 2010). The Sorgenfrei-Tornquist Zone thus acted as a hinge zone during the early Miocene between the uplifting Fennoscandian Shield and the subsiding Danish Basin (Japsen et al., 2018).

Disregarding local effects attributed to intrusive activity in East Greenland (Japsen et al., 2021a), the C7 episode has no counterpart in Greenland, implying that the forces driving this episode originated from intraplate stress transmitted across the Eurasian plate (Japsen et al., 2016). A possible source for such stress could be the early Miocene–-Present Neohimalayan orogenic phase in Himalaya and southern Tibet (Hodges, 2000; Jiang and Li, 2014). The 'hard' India–Asia collision around 25–20 Ma initiated this phase and coincides with deformation in central Asia (van Hinsbergen et al., 2012; Ullah et al., 2023).

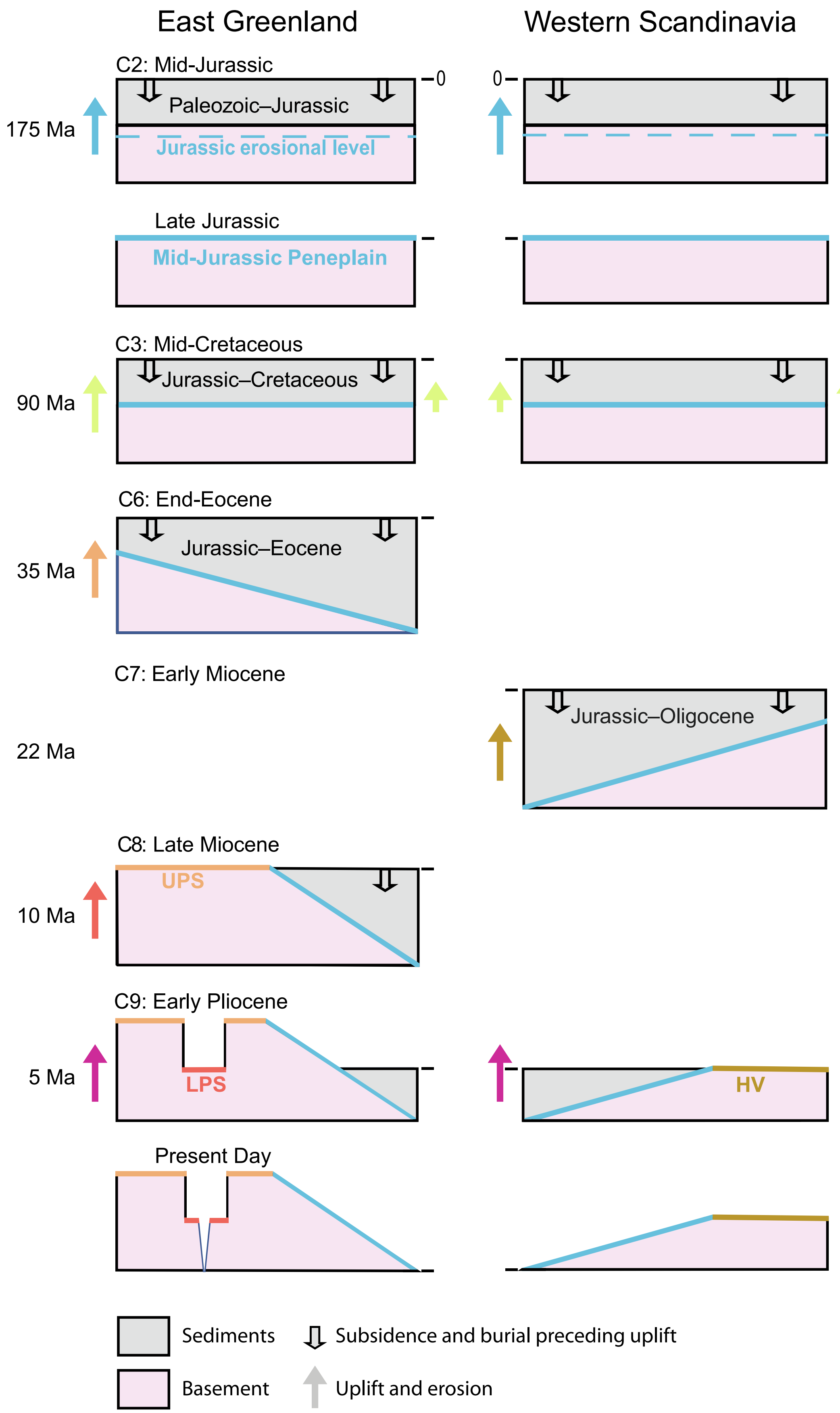

Fig. 9. Cartoon illustrating the Jurassic–Recent history of uplift and subsidence along the margins of the North-East Atlantic. The lack of symmetry in the episodes of uplift and erosion that affected these conjugate margins after break-up, is manifest in the different geometries of the large-scale landscapes on these margins. Episodes of cooling/exhumation C2–C9 defined in Fig. 3. HV: Hardangervidda. LPS/UPS: Lower/Upper Planation Surface.

6.3. Late Miocene episode (C8)

Late Miocene C8 exhumation began at c. 10 Ma in Greenland, the Lomonosov Ridge, Svalbard and the Barents Sea, but is not recorded in Fennoscandia (Fig. 4F). In the interior highlands of North-East Greenland, C8 paleotemperatures can be explained by the incision below the UPS after it was raised from near sea level during Miocene uplift, with little or no regional denudation (fig. 22 of Japsen et al., 2021a). In contrast, over much of the coastal region, an additional section above the present-day summit level must have been present when exhumation began, as C8 paleotemperatures extrapolate to likely values of paleosurface temperatures at elevations well above the present-day topography (entries C8a in the Appendix). As Paleogene basalts are present in the summits at several localities, the missing section there was additional basalt and post-basalt sediments; e.g. 0.5 km or more above the summits (Fig. 7B).

A pronounced increase in the estimated rock uplift since the late Miocene across short distances across the PDMF system indicates differential movements, allowing primarily Miocene sediments to accumulate prior to their removal during late Miocene uplift. The sediments thus accumulated in the coastal zone during a period of crustal extension prior to late Miocene uplift during a compressional phase, which agrees with observations both onshore and offshore North-East Greenland (Price et al., 1997; Hamann et al., 2005; Døssing et al., 2016).

On both margins of Greenland, C8 exhumation initiated the formation of the present relief with incision below the uplifted UPS leading to the development of the Lower Planation Surface (LPS; Figs. 8C,E3, 9C8; see reviews by Bonow and Japsen, 2021). Prior to late Miocene uplift, the terrain across Greenland was low-lying, dominated by the UPS (that had been graded to sea level) or by the subsiding coastal regions where Miocene sediments had accumulated. Modelling of the Greenland ice sheet shows that glaciers could not have formed in the Miocene prior to C8 uplift because of the low absolute relief at that time (Solgaard et al., 2013).

There are no known occurrences of Miocene sediments onshore Greenland, but off North-East Greenland, massive shelf progradation occurred above a distinct angular unconformity, the intra-Miocene unconformity (IMU; Hamann et al., 2005; Berger and Jokat, 2008; Døssing et al., 2016) with an estimated middle to late Miocene age (15–10 Ma; Døssing et al., 2016). The IMU marks the termination of synrift deposition in the deep-sea basins, linked to the onset of late Miocene uplift and massive shelf progradation on the North-East Greenland margin combined with glacial erosion and successive advances of the Greenland ice sheet onto the shelf (Døssing et al., 2016). As the IMU marks the onset of onshore uplift and consequent offshore progradation, it can be dated to about 10 Ma (Japsen et al., 2021a). Late Miocene uplift in North-East Greenland correlates with the merging of the Mohns and Knipovich Ridges to form a continuous plate boundary in the northernmost Atlantic, likely triggered by plate tectonic forces (Døssing et al., 2016; Petersen, 2021). Offshore North-West Greenland, a regional unconformity of late Miocene age is related to slope instability and widespread shelf-margin erosion, suggested to be related to C8 uplift and erosion (Knutz et al., 2015; Gregersen et al., 2022).

Elevated plateaus at 1 km above sea level (a.s.l.) characterize the landscape on northern Svalbard (Fjellanger and Sørbel, 2005; Dallmann, 2015; Dörr et al., 2019). The plateaus are erosion surfaces that cut across Paleogene and older rocks below remnants of a once coherent cover of late Miocene lavas, the Seidfjellet Fm. The configuration of these plateaus is comparable to those in East Greenland, where mid-Miocene basalts rest on the regional peneplain, the UPS (Storey et al., 2004; Bonow et al., 2014). Given the synchroneity of uplift episodes in North and East Greenland and Svalbard at 35 and 10 Ma, it seems likely that a similar sequence of events shaped the basalt-covered plateau in northern Svalbard. Late Miocene exhumation also affected the Barents Sea, but there the end-result was a submerged shelf (Green and Duddy, 2010).

Japsen et al. (2021a) speculated that the asymmetric history of late Miocene uplift across the North-East Atlantic could be explained by changes in the absolute motion of the North American Plate at that time. Sea-floor spreading rates between Eurasia – North America and Nubia – North America varied modestly from 20 to c. 8 Ma but slowed down by c. 20% between 8 and 5 Ma (Merkouriev and DeMets, 2008; DeMets et al., 2015; Iaffaldano and DeMets, 2016). These changes coincide with a well-documented change in Pacific absolute plate motion between 10 and 6 (Cande and Stock, 2004). Iaffaldano and DeMets (2016) therefore argued that the absolute motions of North America had changed, linked to the late Neogene dynamics of the Pacific plate.

Early and late Miocene uplift and erosion of the landmasses and the adjacent basins in the North-East Atlantic are manifest in inclined Paleogene and older beds, truncated by erosional unconformities offshore Greenland and Scandinavia (Fig. 2; Japsen and Chalmers, 2000).

6.4. Early Pliocene episode (C9)

Early Pliocene C9 exhumation (beginning c. 5 Ma) is documented by AFTA data from West and North-East Greenland, the Danish Basin and from the deep OTN boreholes in Finland. Uplift of similar timing was inferred to explain the high elevation of the Miocene peneplains in SE Greenland and southernmost Norway (Japsen et al., 2014, 2018).

C9 uplift amplified by isostatic response to the subsequent fluvial and glacial carving (up to 500 m uplift of the Scandes; Medvedev and Hartz, 2014), led to re-exposure of tilted Mesozoic peneplains with hilly relief along the coasts of Greenland, Norway and south-western Sweden at elevations below the raised Miocene surfaces (Figs. 6B,C, 8A,D,E, 9C9; Bonow et al., 2006b; Japsen et al., 2006, 2018, 2021a; Lidmar-Bergström et al., 2013; Bonow and Japsen, 2021). Offshore North-West Europe, a regional intra-Neogene (c. 4 Ma) unconformity developed in response to pre-glacial uplift and tilting of the continental margin (Stoker et al., 2005). Stoker et al. (2005) showed that the onset of progradation predated significant high-latitude glaciation by c. 1 Myr and extensive northern hemisphere glaciation by at least 3 Myr.

The presence of two elevated peneplains, UPS and LPS, that were graded to sea level in post-basalt time in West and East Greenland, can be explained by the three episodes of post-break-up uplift that affected the region, the end-Eocene C6, the late Miocene C8 and the early Pliocene C9 episodes (Fig. 9; Japsen et al., 2014). Also in the central part of northern Greenland, below the Greenland ice sheet, analysis of a subglacial valley network leads to definition of two phases of incision, overlapping with the C8 and C9 episodes, below a low-relief surface that we interpret to correspond to the UPS in agreement with the thermal history interpretation for the GISP-2 core (Fig. 7C; Paxman et al., 2021). On both margins, the UPS and LPS thus reached their present elevation after early Pliocene uplift, leading to the formation of the modern relief by incision of valleys and fjords below the LPS (Fig. 8C).

The late Cenozoic mountain building in Greenland therefore augmented the effects of the climatic deterioration leading to the Northern Hemisphere glaciations. Without the Pliocene phase of uplift the Greenland ice sheet would have been more sensitive to the changes in climate over the past millions of years (Solgaard et al., 2013). Rivers, not glaciers, dominated the landscape during the formation of the LPS in the late Miocene (Fig. 8C).

In East Greenland, the LPS is generally at 1 km a.s.l. north of 70^0N, but the surface reaches 2 km a.s.l. along Blosseville Kyst ('coast'), where the highest peak in Greenland, Gunbjørn Fjeld, reaches 3.7 km a.s.l. (Fig. 4F). As Blosseville Kyst is the part of Greenland closest to Iceland, it is thus possible that dynamic support from the Iceland Plume since 5 Ma led to this extreme elevation due to outward-flowing asthenosphere extending beneath the continental margins (Rickers et al., 2013; Japsen et al., 2014). This assertion matches the results of Steinberger et al. (2015) who used a mantle-flow model to show that dynamic topography reaches a maximum of 1.2 km for Greenland along Blosseville Kyst.

On the conjugate margin, post-Miocene uplift in southern Norway raised remnants of the Miocene peneplain to an elevation of c. 1.2 km but only to c. 150 m in southern Sweden (Figs. 4F). As in Greenland, it is possible that dynamic support from the Iceland Plume contributed to the Pliocene uplift, and thus to the lateral variation in the elevation of the Miocene surfaces (Japsen et al., 2018). This notion is supported by the observation that Pliocene uplift affected the Baltic Shield as well as the Danish Basin, presumably because asthenospheric flow extended below both regions. In contrast, during the early Miocene the Sorgenfrei-Tornquist Zone acted as a hinge zone between the uplifting shield and the subsiding Danish Basin (Japsen et al., 2018). The synchroneity of the Pliocene uplift episodes along the conjugate margins of the North-East Atlantic indicates immediate, far-field transmission of momentum at the base of the lithosphere through the effects of mantle convection (Bunge et al., 1996).

7. Alternative interpretations

Some authors have argued that the mountains in North-East Greenland and Scandinavia are remnants of the Caledonian mountains (Nielsen et al., 2009; Pedersen et al., 2012, 2016, 2018; Schiffer et al., 2016). However, the highest mountain in Greenland (Gunbjørn Fjeld) is comprised of Paleocene basalt, and the high terrain in East Greenland south of 70°N, as well as West Greenland, is outside the Caledonian Orogen (Henriksen et al., 2009). In addition, post-Caledonian sediments rest on the basement within the former orogen where base-Permian, mid-Jurassic and Cenozoic peneplains also occur (Haller, 1971; Larsen, 1988; Surlyk, 2003; Bøe et al., 2010; Lidmar-Bergström et al., 2013; Bonow and Japsen, 2021). These observations testify to a history of episodic uplift and subsidence rather than to a history of continuous exhumation since the Caledonian Orogeny (Fig. 7A; Japsen et al., 2021a; Lidmar-Bergström and Bonow, 2009; Chalmers et al., 2010; Green et al., 2013, 2022b; Japsen et al., 2012b, 2013).

In addition, Rasmussen (2019) pointed out that Scandinavia provided a limited sediment flux towards the west during the Eocene, whereas sediments from the Shetland Platform were flushed eastwards into the northern North Sea Basin. Rasmussen (2019) thus found it more likely that the Scandinavian area did not form a high relief at that time as the climate in the two source areas was similar (and therefore differences in climate cannot explain the differences in sediment input). In fact, southern Scandinavia may have been below sea-level in the Eocene (Knox et al., 2010).

Another group of authors have suggested that the high mountains in Greenland and Scandinavia are remnants from Mesozoic rifting and subsequent break-up (Swift et al., 2008; Redfield and Osmundsen, 2013; Jess et al., 2018, 2019). However, these studies ignore the well-documented geological record in Greenland, in particular along Blosseville Kyst, that allows a close insight into the development during and after break-up in the North-East Atlantic. At the Paleocene–Eocene transition, the voluminous Main Basalts (flood basalts) erupted onto a flat-lying lava plain with marine incursions above and below the Main Basalts (Wager and Deer, 1939; Nielsen et al., 1981; Larsen et al., 1989, 2013; Pedersen et al., 1997; Larsen and Tegner, 2006). Subsidence must, therefore, have kept approximate pace with the outpouring lavas, and the land surface at the end of the eruptions must have been close to sea level (Nielsen and Brooks, 1981). The Main Basalts that now make up the summit of Gunbjørn Fjeld therefore reached its elevation of 3.7 km after break-up. A similar development is evident in West Greenland where a km-thick, Paleogene volcanic sequence with interbedded, marine deposits accumulated during post-rift subsidence (Pedersen et al., 2002). Today, the marine deposits are at elevations up to 1.2 km a.s.l. (Piasecki et al., 1992). This shows that the present-day elevated topography of the West Greenland margin is not a remnant of the rifting process but developed later (Japsen et al., 2006, 2012b).

Some authors have argued that highly efficient and extensive glacial and periglacial erosion formed the plateau surfaces along the elevated passive continental margin of Scandinavia (Steer et al., 2012; Egholm et al., 2017; Pedersen et al., 2021). However, these authors did not consider that a similar configuration with elevated plateaus occurs along such margins in all climate zones (Lidmar-Bergström et al., 2000; Bonow et al., 2009; Japsen et al., 2012a; Green et al., 2013). In previously glaciated regions, such plateaus were mainly unaffected during the glaciations owing to cold-based, non-erosive conditions, whereas significant erosion took place predominantly in valleys where the ice was warm-based (Kleman, 2008; Hall et al., 2013). In East Greenland (69°N), the presence of the middle Miocene volcanics of the Vindtop Formation on the UPS documents that the peneplain had formed by middle Miocene, well before the extensive Northern Hemisphere glaciations (Storey et al., 2004; Bonow et al., 2014).

8. Evidence of large-scale vertical movements hidden in landscapes and stratigraphic gaps

Our investigations of the thermo-tectonic history of Greenland and Fennoscandia have revealed a long history involving multiple episodes of subsidence/burial and subsequent uplift/erosion since the collapse of the Caledonian mountains. The episodes of kilometer-scale burial and exhumation discussed here affected areas thousands of kilometers across, far from active orogens (except the Eurekan Orogeny). We have been able to document significant offsets indicating differential, km-scale vertical movements. However, in general, the uniformity of the observed paleotemperatures – also expressed as low-angle unconformities on seismic sections – testify to the regional nature of the processes involved. Yet previous studies have identified only limited aspects of these phenomena and, documentation of missing sections has been questioned (Green et al., 2022a).

We were able to recognize the scale of these episodes because we used methods that allow quantification of missing section that was deposited and removed during intervals now represented by gaps in the stratigraphic record and peneplains of different age. Our studies provide a link between disparate observations such as peneplains at high elevation, the long-term preservation of ancient erosion surfaces, truncated sedimentary strata and sediment wedges prograding away from the continents.

9. Comparison with tectonic events in the Canadian High Arctic

While we focus here principally on Fennoscandia and Greenland, it is interesting to note that the episodes discussed in in this paper coincide with many of the large-magnitude sequence boundaries in Canadian High Arctic (north of 68^0) identified by Embry et al. (2018) and interpreted as representing episodic tectonics (see Fig. 3 of Japsen et al., 2023). In particular, the four most recent of those boundaries, at 5, 12, 23 and 34 Ma, correlate remarkably closely with episodes C9, C8, C7 and C6. Boundaries at 42 and 52 Ma are not recognized in data from Fennoscandia and Greenland and may represent more local Eurekan tectonics, but the 62 and 68 Ma boundaries in Arctic Canada overlap with episodes of cooling defined by AFTA, and we have therefore adopted the well-defined timing from the work of Embry for our episodes C5 and C4. Moving further back in time, episodes C3, C2, C1 and C0 are all matched by events defined by Embry et al. (2018), although a much larger number of boundaries are not resolved by the AFTA data. This is probably due, at least in part, to the difficulty in detecting earlier episodes in AFTA data which are partially or totally overprinted by later events. It may also reflect the fact that AFTA only records large-scale events, involving kilometer scale exhumation, whereas the stratigraphic record allows finer scale revelation, as well as recording eustatic effects.

We can conclude that the episodes detected from AFTA data in Fennoscandia and Greenland also left their mark in Arctic Canada. We also note that the 4 most recent episodes defined in this study are also represented by sequence boundaries in the stratigraphic record along the offshore NW Atlantic margin from south of Ireland to the northern tip of Norway (Stoker et al., 2005). These observations from disparate regions further illustrate the regional extent and the tectonic origin of the episodes of exhumation discussed in this paper.

The work of Embry et al. (2018) documents the existence of gaps throughout the stratigraphic record, but our study emphasizes that the large-magnitude sequence boundaries represent tectonic episodes involving deposition and erosion of substantial thicknesses of sediment (Green et al., 2022a).

10. Summary of regional episodes of post-Caledonian exhumation

C0, C1, C2: Late Carboniferous, Middle Triassic and mid-Jurassic exhumation affected Greenland, Svalbard and Fennoscandia with some time variations (C2 is not resolved in Finland). We find it unlikely that exhumation at three broadly similar times, across our wide study area and in disparate locations across the earth should be a coincidence and conclude that exhumation during these episodes are manifestations of global processes related to the break-up of Pangea. Exhumation during these episodes provided thick siliciclastic wedges to adjacent basins and resulted in the formation of sub-Permian, mid-Triassic and mid-Jurassic peneplains prior to marine transgressions. Data from the deep OTN boreholes allow us to establish that a kilometer-thick sedimentary cover was present above the supposedly stable craton in Finland in late Carboniferous. The duration of C2 exhumation was only about 5 Myr based on the age of the sediments that onlap the mid-Jurassic peneplain.

C3: Mid-Cretaceous exhumation affected wide parts of the study area and coincided with the inversion of the Sorgenfrei-Tornquist Zone. This episode resulted in the formation of a deeply weathered, mid-Cretaceous peneplain over large parts of Sweden and Finland and in tilting of the Jurassic peneplains in Greenland and Norway. The episode may be linked with changes in the relative motion between the European and African plates at *c*. 90 Ma, which resulted in intraplate basin inversion and basement thrusting in central Europe.

C4, C5: Maastrichtian exhumation affected the North American Arctic, the Lomonosov Ridge, Svalbard and the Barents Sea, parts of Greenland, both onshore and offshore. The uplift probably reflects doming above the rising Iceland Plume. The mid-Paleocene impact of the plume at the base of the lithosphere under Greenland contributed to the onset of sea-floor spreading west of Greenland and thus to the Eurekan Orogeny, that affected wide areas across the Canadian High Arctic, North Greenland and Svalbard involving inversion of fault zones, thrusting, formation of foreland basins and of the West Spitsbergen Fold Belt.

C6: End-Eocene exhumation interrupted the Eocene regime of subsidence and burial across the region. The episode involved reverse faulting and led to formation of a peneplain along both margins (and apparently across central parts) of Greenland, the Upper Planation Surface, UPS. An end-Eocene unconformity offshore North-West Europe reflects a significant change in basin configuration. The episode coincided with a minimum rate of sea-floor spreading in the North-East Atlantic, indicating substantial alterations in the stress regime. These conditions may be related to changes in the motion of Africa relative to Europe.

C7: Early Miocene exhumation affected Fennoscandia, and the offshore sedimentary basins of North-West Europe, but there is no evidence of regional C7 exhumation in Greenland, implying that the forces driving this episode originated from intraplate stress transmitted across the Eurasian Plate. The tectonic changes in the early Miocene caused a sudden influx of deltaic sediments to the Danish Basin, transported by braided rivers originating in the uplifting Scandinavian hinterland. The exhumation resulted in formation of a Miocene peneplain, of which remnants are preserved in southern Norway and southern Sweden and offshore Norway as a base-Miocene unconformity.

C8: Late Miocene exhumation affected Greenland, the Lomonosov Ridge, Svalbard and the Barents Sea, but not Fennoscandia. The exhumation onshore caused massive shelf progradation offshore Greenland and initiated the formation of the present-day relief by raising the low-lying UPS and thus to incision below this peneplain, leading to the development of the Lower Planation Surface, LPS, on both margins of Greenland. A similar sequence of events may have shaped the basalt-covered plateau in northern Svalbard. The asymmetric history of late Miocene uplift across the North-East Atlantic may be related to changes in the absolute motion of the North American Plate.

C9: Early Pliocene uplift affected wide parts of the region and in particular raised the Cenozoic peneplains along the margins of Greenland and Scandinavia (amplified by isostatic response to erosion). This led to re-exposure of the tilted, Mesozoic peneplains along the margins and to formation of the modern topography by incision of valleys and fjords below the Cenozoic peneplains. Dynamic support from the Iceland Plume possibly led to this phase of uplift due to outward-flowing asthenosphere extending beneath the conjugate margins.

11. Concluding remarks

The observations presented here provide key insights into the nature of the processes that drive the episodes of exhumation. In contrast to the widely accepted paradigm of slowly cooled basement terrains, we have shown that the duration of the uplifts can be very short, only 5 Myr (or 2 Myr according to Embry et al., 2018).

As we have argued specifically for the C0, C2 and C4 episodes, the onset of exhumation in these episodes may reflect doming above plumes upon their arrival in the upper mantle prior to impact at the base of the lithosphere (Campbell, 2007). This interpretation furthermore agrees with the notion that the C0 to C2 episodes reflect disintegration of the supercontinent Pangea following accumulation of mantle heat beneath the supercontinent. Furthermore, the time intervals between the C0, C1 and C2 episodes are about 70 Myr, matching predictions that large-scale mantle movements evolve on timescales on the order of 50 to 100 Myr (Bunge et al., 1998).

However, we also find that several episodes are coeval with changes in plate motion, linked to far-field stress induced by events outside our study area, notably episodes C3, C6, C7 and C8 (Ziegler et al., 1995; Cloetingh and Burov, 2010).

Finally, we hypothesize that C9 uplift of the conjugate continental margins in the North-East Atlantic may be explained by shear forces evolving at the base of the lithosphere by pressure-driven asthenospheric flow from the Iceland Plume (Colli et al., 2014; Hoggard et al., 2021; Vilacís et al., 2022).

In summary, we find that the vertical movements of the surface of the earth reflect a range of processes driven by plate-tectonic forces, either lithospheric or sub-lithospheric. The timing, extent and geological characteristics of these vertical crustal movements provide constraints that hopefully will form the basis for developing quantitative models of the underlying geodynamic processes.

CRediT authorship contribution statement

Peter Japsen: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Paul F. Green:** Methodology, Investigation, Writing – review & editing. **James A. Chalmers:** Investigation, Writing – review & editing. **Johan M. Bonow:** Methodology, Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data are available in supplementary files published together with the cited papers.

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Appendix A. Supplementary data

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