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The High Plains of Southern Norway: Result of Late Mesozoic – Cenozoic Episodic Tectonics

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Abstract The origin of the mountains of Norway (the Scandes) is controversial. Here we show that the high-level landscape of the Southern Scandes consists mostly of three extensive, low-relief surfaces separated by escarpments. The surfaces extend across 90,000 km^2 and cut across rocks of different lithologies and post-date the Jurassic surface on the slopes of the Southern Scandes. The surfaces are peneplains graded by river erosion to a base level of sea level during the Late Cretaceous, Paleocene and Miocene. They were all subsequently slightly folded, tilted and uplifted to their present elevations of 1000–1400, 1300–1700 and 1600–1900 m, forming a landscape with distinct steps. The final uplift began in the early Pliocene and caused incision of fluvial valleys and exhumation of the Jurassic surface stripped from its protective cover of Jurassic and younger sediments. Many fluvial valleys were reshaped into glacial valleys and fjords during the Quaternary, while the stepped peneplains kept much of their pre-glacial appearance. The Scandes have not remained high since the Caledonian Orogeny, they are not shaped by footwall uplift and the plateau surfaces are not the result of glacial erosion. The repeated episodes of subsidence and uplift, burial and exhumation that shaped the high-level landscape of the Southern Scandes were driven by sub-lithospheric forces and intra-plate stress. This landscape resembles the elevated passive continental margins (EPCMs) that occur globally in all climate zones. The observations reported here provide important constraints on studies of the tectonic development of western Scandinavia and other EPCMs.

Executive Editor:
Graeme Eagles
Associate Editor:
Claudio Salazar-Mora
Technical Editor:
Mohamed Gouiza

Reviewers:
Tony Doré
Reviewer 2 (Anonymous)

Submitted:
8 July 2025
Accepted:
27 March 2026
Published:
1 May 2026

1 Introduction

"Passive continental margins typically show a continuous subsidence during their evolution. As sediment covers and masks the old rift topography–a smooth, broad, gently seaward-dipping coastal plain– continental shelf is generated" (*Frisch et al.*, 2022). Many passive continental margins – in all climate zones – are, however, not typical of this definition. Elevated passive continental margins (EPCMs) are characterized by mountain ranges 2 km or more high containing elevated plateaus at 1 to 2 km or more above sea level (a.s.l.) (*Japsen et al.*, 2012a). They commonly contain low-relief surfaces well above sea-level, are separated from a coastal plain by one or more escarpments, are dissected by deep valleys and, offshore, post-rift sediments typically dip away from the coast and have been eroded (*Jensen and Schmidt*, 1992; *Thomas*, 1995; *Japsen and Chalmers*, 2000; *Lidmar-Bergström et al.*, 2000; *Japsen et al.*, 2012a; *Green et al.*, 2013, 2018).

The mountains in southern Norway south of the Møre-Trøndelag Fault Complex (MTFC), the Southern Scandes, have the characteristics of an EPCM (Figure 1). For many years, their large-scale landforms have been described as consisting of high plains incised by deep valleys and with high altitudes close to the Atlantic Ocean. *Reusch* (1901) pointed out that the high plains had to be old compared to the deep valleys incising them and coined the term "palaeic surface" for them (Figure 2a).

Lidmar-Bergström et al. (2000, 2013) summarized older work (*Reusch*, 1901; *Wråk*, 1908; *Ahlmann*, 1919, 1941; *Holtedahl*, 1954; *Gjessing*, 1967) and described the contrast between the elevated, sub-horizontal plains (the 'palaeic relief', Figure 2a) and the dipping flanks of the Southern Scandes (Figure 2b). Many studies of the origin of the Southern Scandes have not considered these striking features (*Redfield et al.*, 2005a; *Nielsen et al.*, 2009; *Redfield and Osmundsen*, 2013; *Pedersen et al.*, 2016; *Egholm et al.*, 2017; *Makushkina et al.*, 2025; *Balling et al.*, 2026), but other studies have, however, argued for a sequence of events that may explain these aspects of the Southern Scandes (*Lidmar-Bergström et al.*, 2000; *Japsen et al.*, 2018, 2024; *Green et al.*, 2013, 2022).

The Norwegian margin is thus typical of many EPCMs and the discussion about the origin of the Norwegian mountains is also typical of the decade-long debate about the origin of such margins elsewhere on the planet. Some

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studies argue that these elevated margins are remnants of rift shoulders from the time of rifting or continental break-up (*Ollier and Pain*, 1997; *Gernon et al.*, 2024), while other investigators suggest that EPCMs are young features (*Lidmar-Bergström et al.*, 2000; *Green et al.*, 2013). The Norwegian mountains is an obvious test site for this debate.

In this paper we present the first detailed maps of the palaeic relief of the Southern Scandes that show the presence of three extensive plains at different altitudes. We show evidence that these surfaces were formed by fluvial erosion graded to sea level and are therefore peneplains. We date the formation of the peneplains to the Cretaceous and Cenozoic by correlating them with periods when large amounts of sediment originating from Norway accumulated in the basins surrounding it. These episodes agree with dates of onset of cooling and exhumation from apatite fission-track analysis (AFTA; *Green et al.*, 2022). We also show evidence that the final uplift of the peneplains to their present altitudes started before the onset of glaciation in Norway and we suggest some possibilities for the mechanisms that initiated the exhumations that led to their formation.

2 Study Area

The Southern Scandes is an elongated topographical dome centred in southern Norway whose highest summit is at 2468 m a.s.l. located in the Jotunheimen Mountains (Figure 1). The dome terminates to the north in an alpine landscape immediately south of the MTFC. The landscape between 1000 m and 2000 m (the palaeic relief) consists of high-level plains separated by escarpments (*Ahlmann*, 1919; *Lidmar-Bergström et al.*, 2000). Areas above 2000 m consist of arêtes and horns, alpine landscapes, formed by glacial and periglacial processes. Slopes, deeply incised by valleys and fjords, dip west, south and east below the palaeic relief. Offshore, these slopes dip below sediments that rest on crystalline basement south and west of the Southern Scandes (*Sigmond*, 2002). The deep and narrow valleys are incised predominantly below the lowest level of the palaeic relief at about 1000–1200 m a.s.l. and parts of some valleys have retained their fluvial character despite the later Cenozoic glaciations (*Wråk*, 1908; *Lidmar-Bergström et al.*, 2000; *Bonow et al.*, 2003). The Scandes are located east of the North Sea Basin, where rifting took place in the Jurassic, and close to the NE Atlantic Ocean, where sea-floor spreading started in the earliest Eocene (*Gaina et al.*, 2017).

2.1 Bedrock Geology

The Southern Scandes south of 63°N consist of four geological provinces that to varying degree were affected by the mid-Silurian – early Devonian Caledonian Orogeny (Figure 3; *Sigmond*, 2002; *Gee et al.*, 2008). (i) A SW–NE-trending belt of Caledonian nappes thrust over the basement. North-West of this belt are (ii) Proterozoic high-grade metamorphic rocks that were folded and metamorphosed in the Caledonian event, and on which Devonian sediments accumulated within extensional basins formed during the Early Devonian collapse of the Caledonian mountains (*Gee et al.*, 2008; *Wiest et al.*, 2021). South-East of the Caledonian thrust belt is (iii) Proterozoic high-grade metamorphic basement unaffected by the Caledonian Orogeny, which is separated from its continuation eastward into Sweden by the Permo–Carboniferous Oslo Rift. The Oslo Rift contains Cambrian–Silurian sediments, a complex succession of Permo–Carboniferous volcanic and intrusive rocks and Permian sediments as well as Lower Triassic granites (*Sigmond*, 2002; *Larsen et al.*, 2008). Between the Caledonian nappes and the Proterozoic basement are (iv) Cambro–Ordovician sediments metamorphosed to low grade (phyllites) during the Caledonian orogeny. The phyllites acted as a detachment for the lowermost nappes.

Ice sheets in Fennoscandia expanded considerably from 2.7 Ma, and the expansion included 40 to 50 phases of wide-spread glaciation (*Mangerud et al.*, 2011; *Mangerud*, 2025). All these glaciations have eroded the landscape, transforming valleys to fjords, but at the same time the high lying plateaus have mainly been unaffected by erosion (*Fredin et al.*, 2013; *Hall et al.*, 2013; *Hall and Kleman*, 2014).

There is little stratigraphic evidence available onshore about the geological history of the study area between the cessation of Carboniferous–Permian volcanism and the onset of pre-glacial river erosion, with the exception of the Brumunddal Sandstone of an estimated early Permian age in the northern part of the Oslo Rift (*Larsen et al.*, 2008) and Jurassic outliers along the coast (*Sigmond*, 2002; *Bøe et al.*, 2010, Figures 1, 3).

The Southern Scandes are limited to the north by the MTFC, a 10–50 km wide, steeply dipping Palaeozoic fault complex which was primarily active in the Mesozoic (*Sigmond*, 2002; *Redfield et al.*, 2004, 2005b,a; *Watts et al.*, 2023) (Figures 1, 3). It consists of a series of WSW- to ENE-trending fault blocks throwing down to the NNW. The blocks between the faults form ridges of bedrock separated by fjords and valleys. The MTFC appears to be the margin of an extensional basin to its NW, a continuation of the Møre Basin offshore (*Brekke et al.*, 2001; *Bøe et al.*, 2010).

Southern Norway is also crossed by the Lærdal-Gjende Fault System (LGFS; Figure 3), a Caledonian-age fault complex that *Andersen et al.* (1999) suggested was active in the mid – late Permian and late Jurassic – early Cretaceous and which, rather than the MTFC, may be the southern limit of Cretaceous extension. If so, the LGFS must have thrown down to the NW.

2.2 Evidence for Post-Caledonian Exhumation

Several low-temperature thermochronology studies in Norway have documented that large thicknesses of rock have been removed across the region during Mesozoic and Cenozoic denudation (*Rohrman et al.*, 1995; *Hendriks et al.*, 2007; *Ksienzyk et al.*, 2014; *Japsen et al.*, 2018; *Hestnes et al.*, 2023). A recent

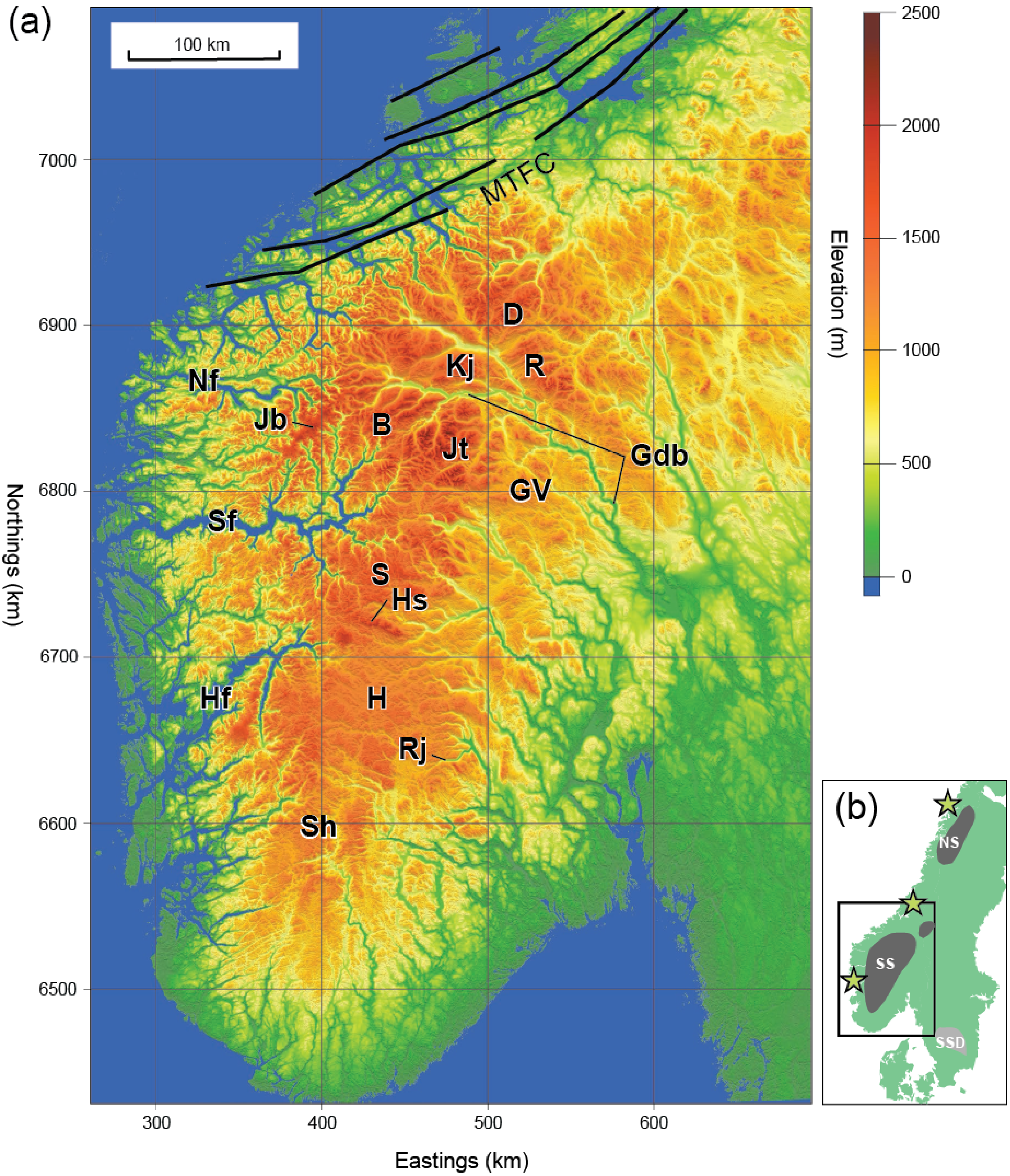


Figure 1 – Topography. (**a**) Topographical map of the study area of the Southern Scandes, which form a north-south elongated dome south of the Møre-Trøndelag Fault Complex (MTFC). The palaeic relief (yellow-red) is clearly distinct from the incised valleys (green). The map projection is UTM Zone 32. (**b**) Scandinavia, showing the location of map **(a)** and the 3 topographic domes described by *Lidmar-Bergström* (1999); *Lidmar-Bergström et al.* (2013). Green stars: Jurassic outliers (*Bøe et al.*, 2010). B: Breheimen. D: Dovrefjell. Gdb: Gudbrandsdalen. GV: Gausdal Vestfjell. H: Hardangervidda. Hf: Hardangerfjorden. Hs: Hallingskarvet. Jb: Jostedalsbreen. Jt: Jotunheimen. Kj: Kjølen. Nf: Nordfjord. NS: Northern Scandes. R: Rondane. Rj: Rjukan. S: Skarvheimen. Sf: Sognefjord. Sh: Setesdalsheiene. SS: Southern Scandes. SSD: South Swedish Dome.

Figure 2 – Landscapes of the Southern Scandes. **(a)** High-level plains west of Hardangervidda (c. 1200 m a.s.l.) cut by a branch of Hardangerfjorden showing that the high plains of southern Norway must be older than the deep valleys incising them (Reusch, 1901). **(b)** Hilly relief on the slopes of the Southern Scandes. The hilly relief has been modified by overriding ice, resulting in enhanced relief; some glacial features have formed, such as a small cirque on the flank of the left-hand hill (Kvernafjellet, 965 m a.s.l., rises 190 m above the lake in the foreground).

synthesis of apatite fission track analysis (AFTA) data and associated thermal history constraints from Precambrian and Phanerozoic rocks across Fennoscandia have provided consistent evidence of rocks that were formerly present but have since been removed (*Green et al.*, 2022). *Japsen et al.* (2024) used AFTA data and geological evidence to show that Fennoscandia, the Danish Basin, Greenland and adjacent regions underwent regional phases of post-Caledonian, km-scale exhumation in the Late Carboniferous, Middle Triassic, mid-Jurassic, earliest Late Cretaceous, Paleocene and Pliocene. Early Miocene exhumation affected only Fennoscandia. These episodes are documented as unconformities in the stratigraphic record and define a history involving repeated episodes of regional burial and exhumation. Here we show that they are also represented by prominent peneplains onshore.

2.3 The Re-exposed Jurassic Surface Defining the Flanks of the Southern Scandes

Despite the limited evidence onshore about the post-Permian history of the study area, there are indications that suggest that the slopes of the Southern Scandes below the palaeic relief is a re-exposed mid-Jurassic peneplain (the Jurassic surface):

- *Lidmar-Bergström et al.* (2013) noted that the hilly bedrock surface on the flanks of the Southern Scandes (Figure 2b) is everywhere located below the plains of the palaeic relief (Figure 4). They argued that this bedrock surface was modified into fracture valleys and hilly relief by chemical weathering in fractures during warm, humid conditions in the Mesozoic and that these landforms had been preserved below a protective cover until their re-exposure following relatively recent uplift, which began in the Pliocene (*Japsen et al.*, 2018).
- The slopes of the Southern Scandes dip from the palaeic relief to the coast and to 1.5 km below sea level offshore where the hilly relief is covered by Upper Jurassic and younger sediments (Figure 5; *Riis*, 1996; *Japsen et al.*, 2018).
- *Japsen et al.* (2018) suggested that the hilly, Jurassic surface was formed as the result of mid-Jurassic exhumation (*Underhill and Partington*, 1993; *Rohrman et al.*, 1995; *Green et al.*, 2022) and that a cover of Jurassic and younger sediments, now restricted to the present-day offshore, probably continued to a present-day altitude of at least 1000 m as late as the Miocene.
- AFTA data from basement samples along the SW coast of Norway, vitrinite reflectance values of the Jurassic outliers near Bergen (*Fossen et al.*, 1997; *Japsen et al.*, 2018; *Green et al.*, 2022) and in the inner parts of Trondheimsfjorden (*Bøe et al.*, 2010; *Weisz*, 1992) indicate burial of the Jurassic surface along the present coast by up to 2 km of sediment prior to early Miocene exhumation (see discussion in *Green et al.*, 2022).

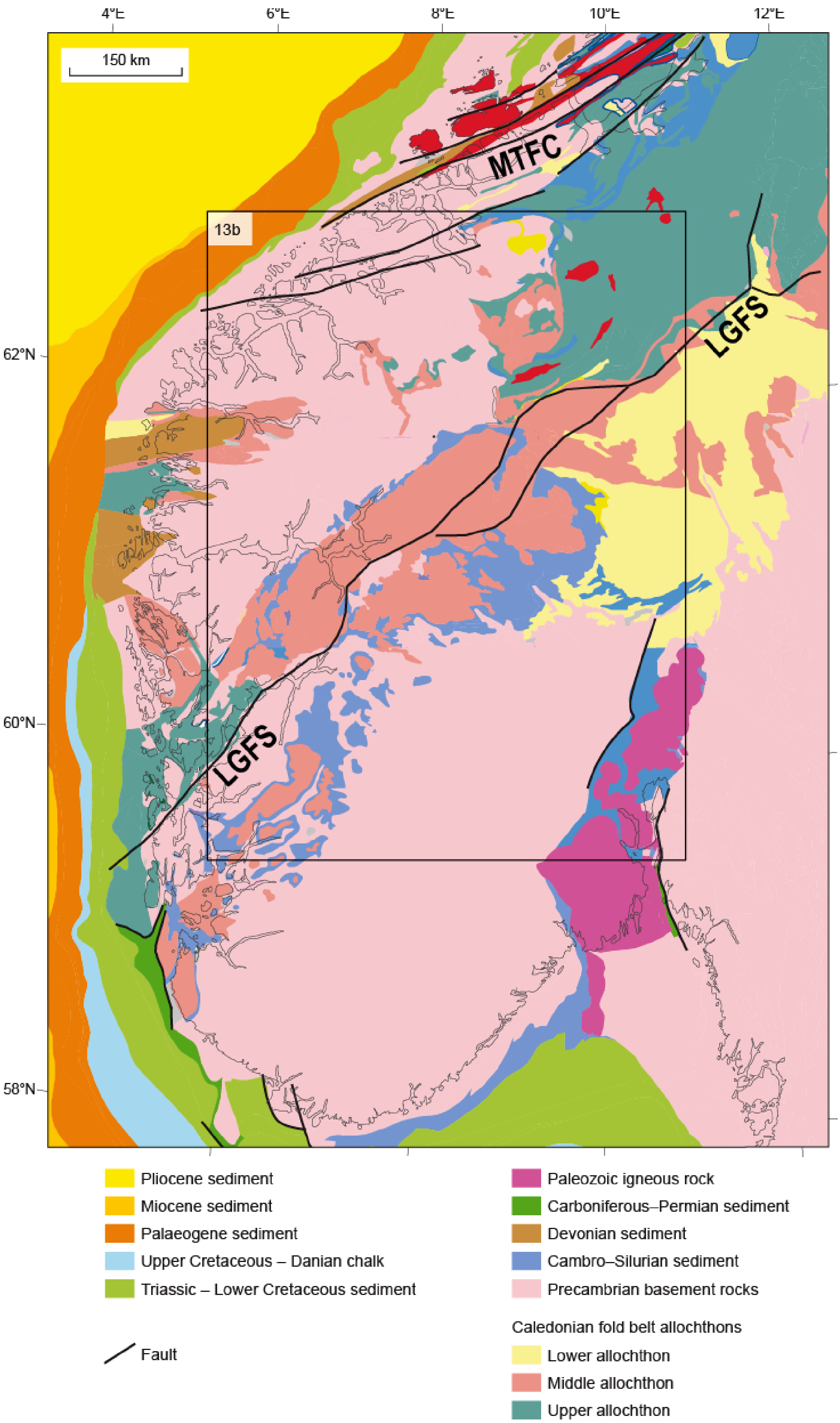


Figure 3 – Main geological features of the Southern Scandes. Map area corresponds to that of Figure 1a. Modified from *Sigmond* (2002) and *Japsen et al.* (2018). The black rectangle shows the location of the map in Figure 11b. LGFS: Lærdal-Gjende Fault System. MTFC: Møre-Trøndelag Fault Complex.

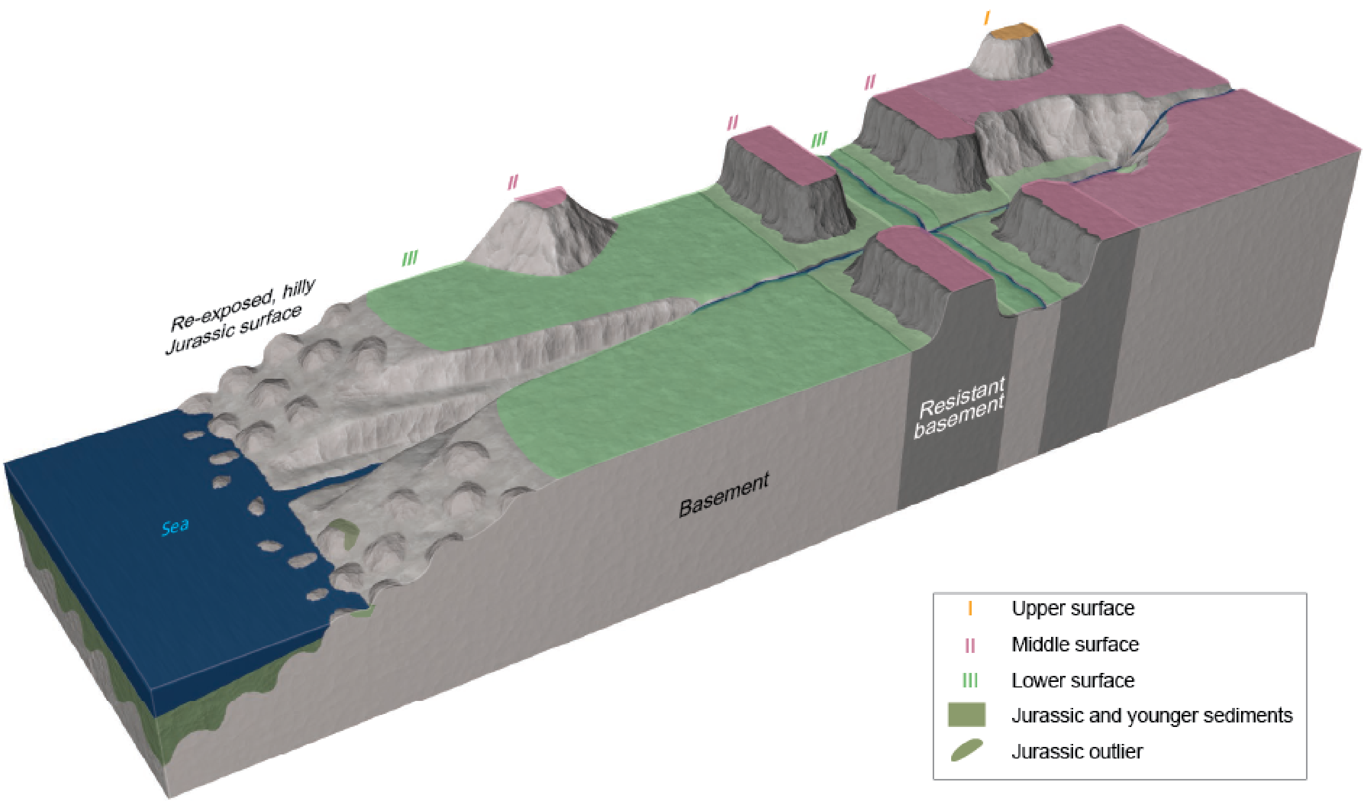


Figure 4 – Conceptual diagram illustrating the present-day configuration of the palaeic relief relative to the Jurassic surface on the flanks of the Southern Scandes (*Lidmar-Bergström et al.*, 2013; *Japsen et al.*, 2018). The illustration is adapted from Figure 14 of *Green et al.* (2013).

- Deep weathering during the Jurassic altered the basement in central Norway, and the weathered surface remained protected by a sedimentary cover until Cenozoic exhumation (*Olesen et al.*, 2023).
- Saprolites in fractured basement have been reported both onshore (*Roaldset et al.*, 1982; *Sørensen*, 1988; *Olesen et al.*, 2007; *Fredin et al.*, 2017) and offshore Norway (*Riber et al.*, 2015, 2016; *Ottesen et al.*, 2022).
- *Fredin et al.* (2017) obtained Norian (Late Triassic) ages from K–Ar dating of authigenic, syn-weathering illite from saprolitic remnants in the coastal zone (strandflat) in SW Norway, suggesting that the surface may originally have been exposed in the Triassic. Northern Europe was a desert in the Norian, so *Japsen et al.* (2018) argued that the weathering probably happened later, during the warm and humid climate that prevailed during the Rhaetian and later periods (*Lidmar-Bergström*, 1982).

Japsen et al. (2024) suggested that the tectonic episode in the earliest Late Cretaceous (*Green et al.*, 2022) resulted in folding of the mid-Jurassic peneplain in Norway and thus in the dip of slopes of the Southern Scandes observed today. This notion provides an explanation for the much higher Mesozoic paleotemperatures (defined by AFTA data) in the central parts of the Southern Scandes compared to locations to the north and south, whereas Miocene paleotemperatures show only minor differences. *Japsen et al.* (2024) argued that the higher values in the Mesozoic episodes in the central region were best explained by larger vertical displacements during the earliest Late Cretaceous episode.

2.4 Development of the Regional Landscape

Lidmar-Bergström (1999) and *Lidmar-Bergström et al.* (2013) discussed the three topographic domes of Scandinavia, viz. the Southern Scandes, the Northern Scandes and the South Swedish Dome (Figure 1b). In the Southern Scandes and the South Swedish Dome, the sub-horizontal surfaces (the palaeic relief and the South Småland Peneplain, respectively) cut off areas of dipping, crystalline basement characterized by undulating hilly relief and fracture valleys formed by weathering during warm and humid climates in the late Jurassic and Cretaceous. They further argued that the elevated planar areas are peneplains formed by rivers eroding to their base level. Successive phases of uplift then raised the surfaces to their present altitudes and each uplift phase initiated the formation of a new peneplain. Such movements result in a landscape as shown in Figure 4 and its development is described in Supplement S5.

Relatively recent uplift of the Southern Scandes led to re-exposure of the Jurassic surface below the extensive plain of Hardangervidda (1000–1200 m a.s.l.; the lowest of the planar surfaces). *Japsen et al.* (2018) adopted this interpretation and used AFTA data to conclude

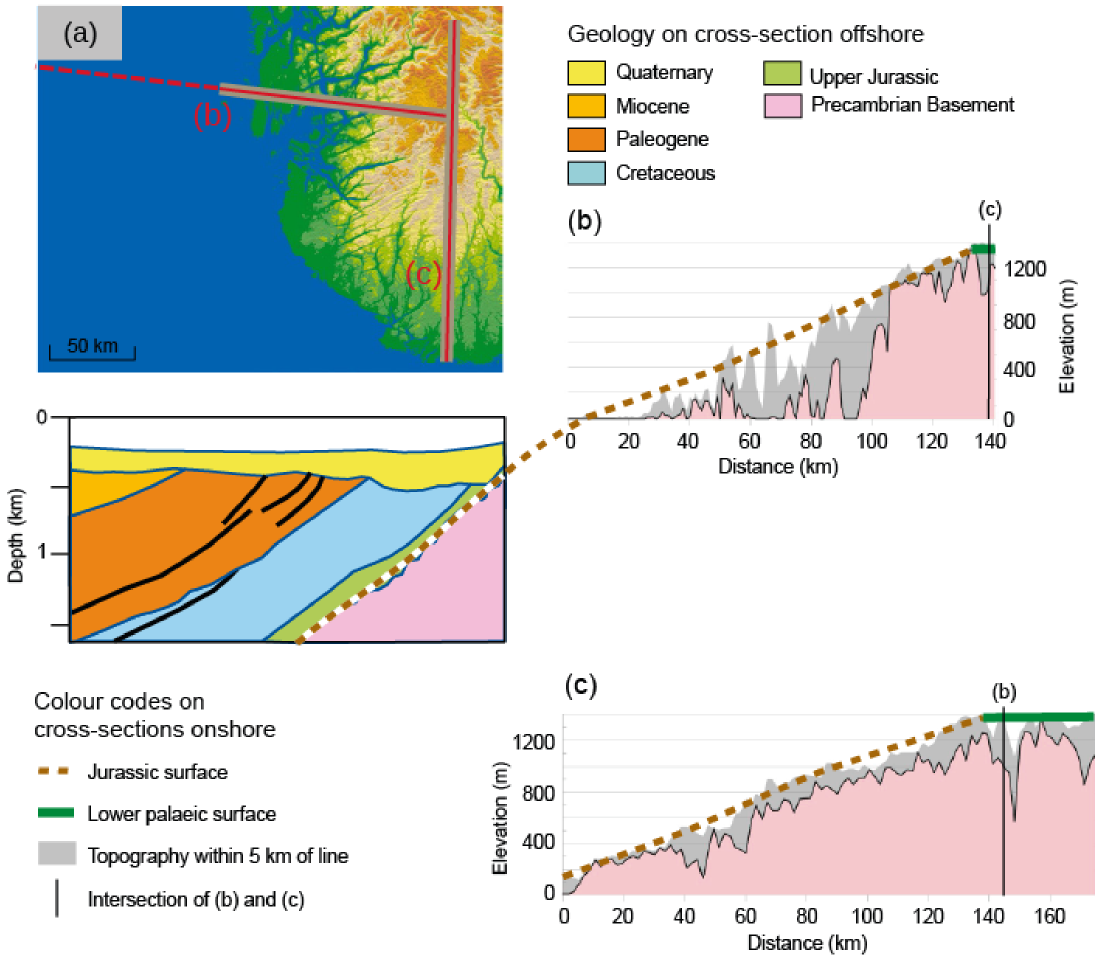


Figure 5 – Evidence that the Jurassic surface offshore continues onshore. (**a**) Part of the map in Figure 1a showing the location of the cross-sections in (**b**) and (**c**). Grey band around the profile lines: the 10-km wide swaths showing maximum altitudes from the cross-sections in **(b)** and **(c)**. (**b**) The left-hand side shows the interpretation of a seismic section (*Japsen et al.*, 2018, Figure 9). The right-hand side shows the altitudes derived from the DEM. Maximum altitudes within a swath 10 km wide are shown in grey. The surface at the base of the sediments is interpreted to continue across the eroded area at lower altitudes to where it is cut-off at an altitude of just under 1400 m by the Lower Palaeic Surface, LPS. The area crossed by the onshore part of (**b**) has been heavily eroded; however, remnants of the Jurassic surface can be interpreted on the maximum altitudes. (**c**) Cross-section from a much less-heavily eroded area than crossed by (**b**). Maximum altitudes within a swath 10 km wide are shown are shown in grey . The Jurassic surface can be continued from close to the intersection with **(b)** down to sea level.

that Hardangervidda is a peneplain remnant graded to near sea-level during exhumation that started in the early Miocene at the same time as areas in both Norway and Sweden were shedding large amounts of sediment to form a large delta in present-day Denmark (*Rasmussen et al.*, 2010; *Rasmussen*, 2014; *Olivarius et al.*, 2014). This interpretation implies that the Miocene peneplain also extended across Jurassic–Palaeogene sediments that covered the hilly relief of the Jurassic surface and protected it until the relatively recent past.

3 Methods and Data

3.1 Principles of Stratigraphic Landscape Analysis

We have extended the results of *Lidmar-Bergström* (1982) and *Lidmar-Bergström et al.* (2013) using the techniques of stratigraphic landscape analysis (SLA) to interpret the palaeic relief. A detailed description of the technique is given by *Green et al.* (2013). In summary, SLA is a method to identify and map low-relief denudation surfaces – horizontal or inclined – (peneplains), that pay little respect to geological structures (e.g., *Davis*, 1899). Such denudation surfaces have been identified in various parts of the world, in areas both glaciated during the Pleistocene and areas not glaciated since the Palaeozoic (*King*, 1967; *Lidmar-Bergström et al.*, 2000; *Green et al.*, 2013; *Bonow and Japsen*, 2021; *Bonow et al.*, 2006a,b, 2014).

SLA is based on the following principles:

1. Peneplains cut continuously across rocks of different age and resistances to erosion, crystalline basement, metamorphic rocks and sediments.
2. Cross-cutting relationships between peneplains and the age of any cover rocks determine their relative ages.

3. Uplift subsequent to formation of a peneplain will cause fluvial incision below the surface. Therefore, even in a terrain of Precambrian bedrock, it is possible to establish a relative denudation chronology where more elevated surfaces predate the surfaces at lower elevation.
4. Peneplains can commonly be correlated with unconformities in offshore sediments (*Japsen et al.*, 2012a, 2018).

Once formed, a regional erosion surface will persist in the landscape for amounts of time dependant on resistance to erosion; a surface eroded into more resistant rocks such as crystalline basement will persist for a relatively long time whereas one eroded into less resistant rocks will be eroded quickly after uplift (*Green et al.*, 2013).

To grade a surface to a base level involves weathering of rocks of different age and resistance, slope processes and transportation of the eroded material by rivers. Fluvial erosion and transportation of materials to base level is thus a fundamental process to form extensive, low-relief surfaces (*Ritter et al.*, 2001). However, the final shape of the peneplain depends on the climatic conditions after its formation and its continued exposure. Weathering of the bedrock during warm and humid climates will result in a hilly relief with thick kaolinitic saprolites along fracture zones, whereas fluvial erosion in dry and/or temperate climates will result in a flat surface. *Green et al.* (2013) therefore defined all surfaces graded to a base level as peneplains, irrespective of whether their detailed present-day form is hilly or flat, and we adopt that definition. In the cases where the sea transgressed a peneplain, base level was sea level and the peneplain was slightly modified by the formation of a transgressive wave-cut platform, as well as being buried and protected from further erosion by depositing sediments (*Japsen et al.*, 2009).

SLA has previously been applied to only a limited area of the palaeic relief in the Scandes (*Bonow et al.*, 2003). However, the combination of a contour map and a grid of profiles derived from a DEM to establish a 3D picture of the large-scale features of the relief has been applied in other areas; e.g. Greenland (*Bonow et al.*, 2006a,b, 2014, 2009), South America (*Bonow et al.*, 2009; *Japsen et al.*, 2012b, 2025) and China (*Liu et al.*, 2019). The maps of these regional landscapes established in this way have provided important insights into the tectonic development of the areas investigated.

3.2 Data and Fieldwork

We used the ASTER Global Digital Elevation Map (ASTER GDEM) as the basis of our study (Figure 1). The elevation model has a spatial resolution of 1 arc-second, i.e. c. 30 m between the data points. It is a product of METI and NASA and the data is publicly available at http://reverb.echo.nasa.gov/reverb. The data at their original resolution show structures inappropriate for this study, such as Quaternary deposits, so the original data were resampled to a rectangular grid of 100 m x 100 m, appropriate to revealing the relevant landscape features. This grid was then used to construct the contour map (Supplement S1) and topographical profiles (Supplements S2 and S3) analysed in this study.

We have carried out extensive fieldwork in southern Norway over many decades and are therefore able to document the landscape of the Southern Scandes not only as contour maps and profiles but also by the many photographs presented here.

3.3 Construction of Maps and Profiles

The first step in the mapping was the construction of a contour map from the DEM. A contour interval of 100 m resulted in a reasonable picture of the general landscape features on the map, such as flats, escarpments, deeply incised valleys and the residual areas between the deeply incised valleys. The resulting map was plotted at a scale of 1:500,000.

We extracted a grid of topographical profiles with a 25-km spacing from the DEM, 18 profiles N–S and 24 profiles W–E. We produced paper plots of the altitude along the profile together with the maximum and minimum elevation within a swath extending 25 km on each side of the centre line at a horizontal scale of 1:500 000 and a vertical exaggeration of 10:1 (Supplements S2 and S3).

3.4 Technique for Mapping of Low-relief Surfaces and Escarpments

We used the 1:500,000-scale contour map as the basis for the mapping. Areas with relatively few contours represent low-relief landscapes and thus possibly represent palaeo-surfaces. We identified a low-relief surface where 100-m contours are spaced more than 1 km apart, corresponding to slopes less than 6.5° (*Bonow et al.*, 2003). We identified the edges of a low-relief surface as locations where widely-spaced contours become more closely spaced, corresponding to slopes of more than 6.5° (Figure 6a). Changes of this type happen at escarpments (where 100-m contours are less than 500 m apart, corresponding to slopes greater than 12° and less commonly where the transition between two surfaces is a slope between 6.5° and 12° (Fig. 6b, blue arrow). Changes in slope angle between 6.5° and 12° also occur on the sides of valleys incised into the surfaces.

We also identified shallow river valleys on the surfaces (Figure 6b) that we interpret as being part of the formation of the surfaces. All of these features may have been modified by ice, but field work suggests that the degree of modification is sufficiently small that their identity is still preserved.

The primary interpretation was carried out on the type of maps shown in Figure 6. We correlated the surfaces from place to place by marking the low-relief surfaces identified from the contour map (Figure 6c) onto the profiles at the appropriate elevations (Figure 7). In low-relief areas, the maximum elevation along the swath

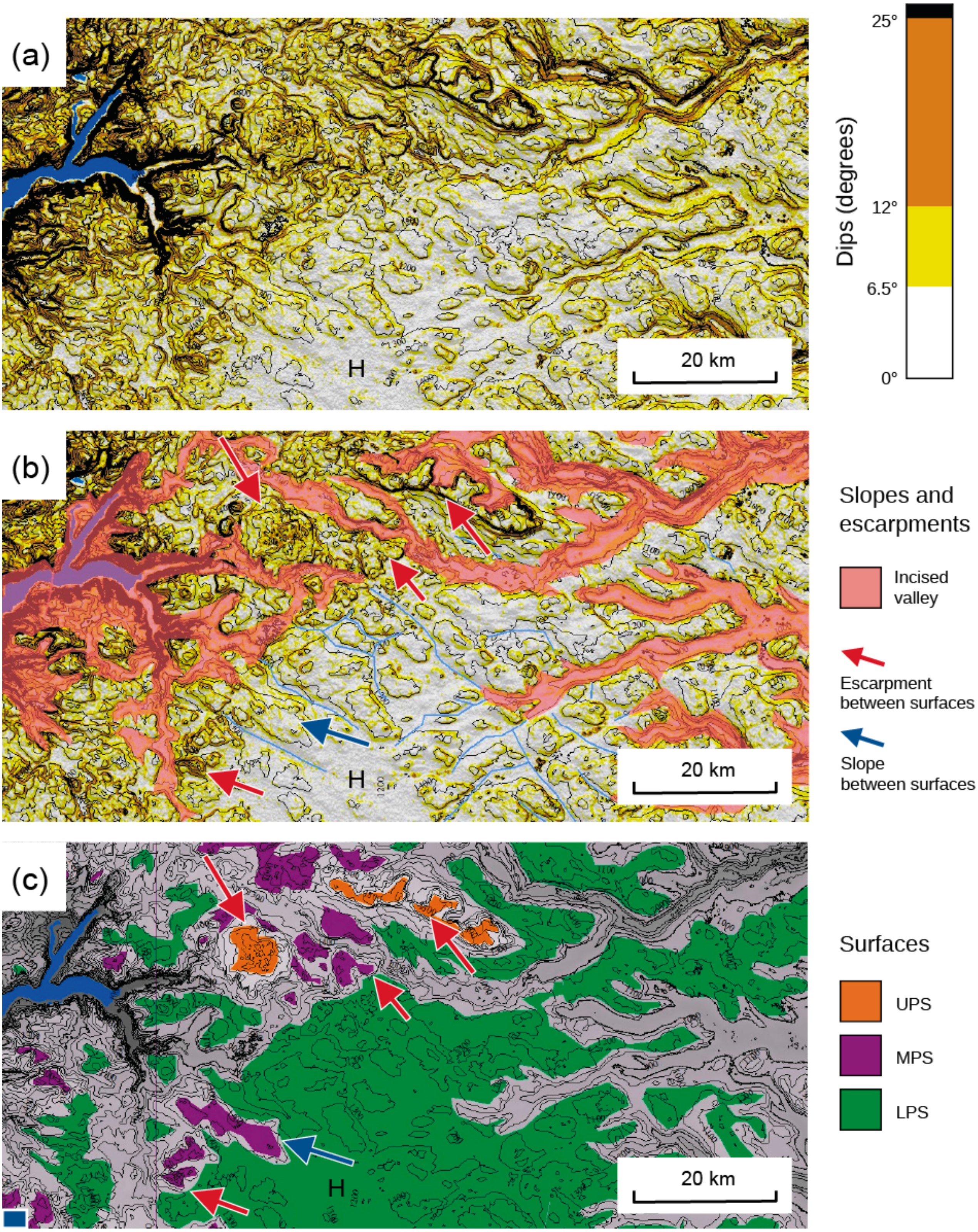


Figure 6 – How the surfaces were interpreted. (**a**) Detail of the 1:500,000-scale contour map used as the basis for the mapping. Contours are heights above sea level at 100 m intervals. Slopes are color-coded as shown in the scale on the right. Areas with slopes less than 6.5° are classified as surfaces (where 100-m contours are spaced more than 1 km apart). Small areas (< ca. 1 km in extent) with slopes between 6.5° and 12° are found within the surfaces, while more extensive areas with slopes between 6.5° and 12° are interpreted as slopes between surfaces. Slopes greater than 12° are interpreted as escarpments or as the margins of valleys incised below the surfaces (where 100-m contours are less than 500 m apart). (**b**) Major valleys incised below the surfaces are coloured pink. Minor river courses on the surfaces are shown with blue lines. Examples of where palaeic surfaces are separated by escarpments are shown with red arrows. A blue arrow shows where two surfaces are separated by a slope. (**c**) Interpreted palaeic surfaces. The location of this map frame is shown in Figure 11a. H: Hardangervidda. LPS, MPS, UPS: Lower, Middle, Upper Palaeic Surface.

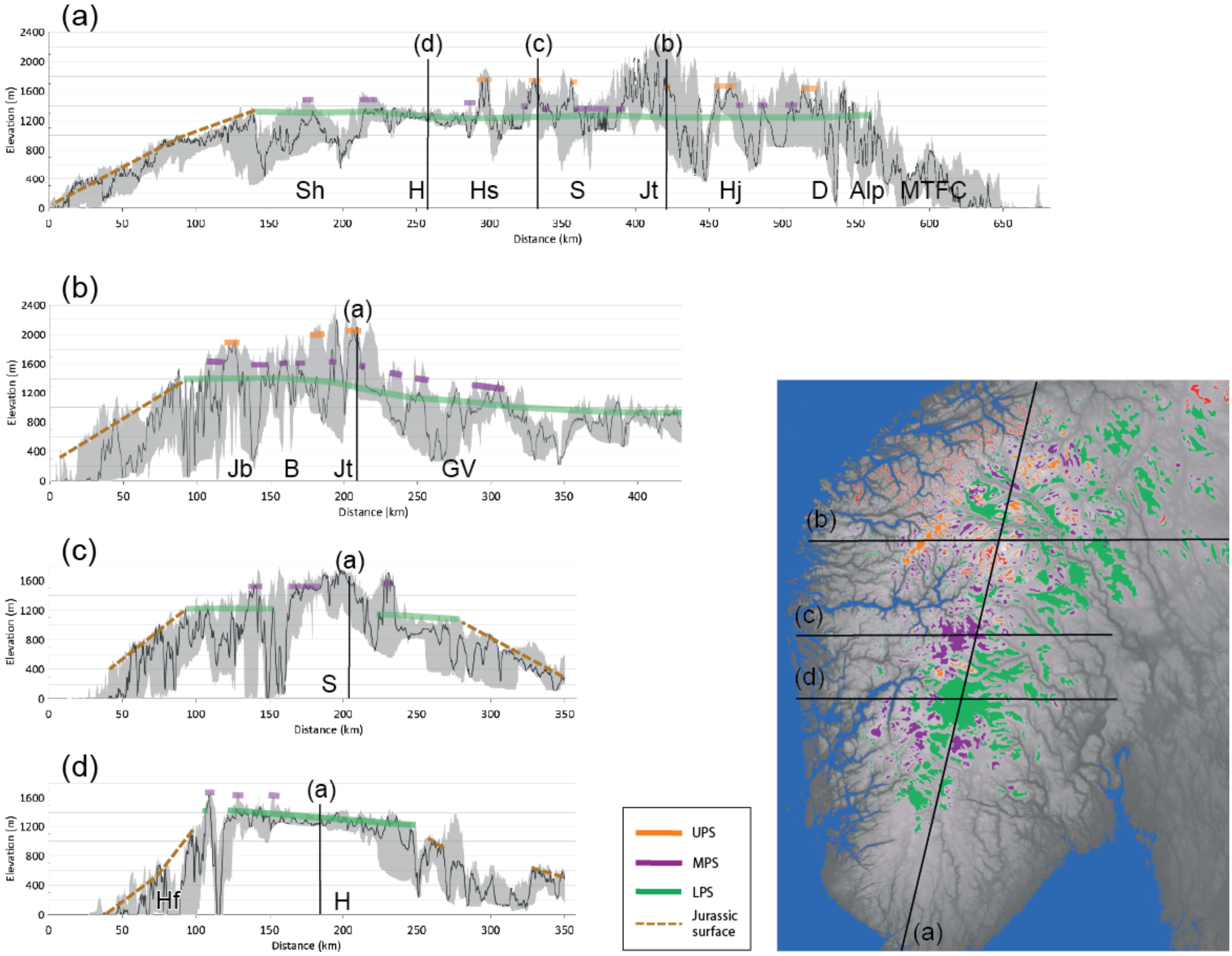


Figure 7 – Regional cross-sections showing interpretations of the palaeic surfaces (profiles (**a**)–(**d**) (vertical exaggeration 30:1). The black lines on the cross-sections show the topography along the cross-section and the grey areas show the maximum and minimum topography within 25 km on each side of the centre line. Preliminary suggestions for the locations of the Jurassic surface on the flanks of the South Scandes are also shown. Note how an extension of the Jurassic surface is cutoff especially by the LPS but also by the MPS. Cut-offs of this type indicate that the palaeic surfaces are younger than the Jurassic surface. The black lines in (**e**) show the locations of the cross-sections. Map projection UTM zone 32. Alp: Alpine relief. B: Breheimen. D: Dovrefjell. GV: Gausdal Vestfjell. H: Hardangervidda. Hf: Hardangerfjorden. Hj: Hardangerjøkulen. Hs: Hallingskarvet. Jb: Jostedalsbreen. Jt: Jotunheimen. MTFC: Møre-Trøndelag Fault Complex. S: Skarvheimen. Sh: Setesdalsheiene. LPS, MPS, UPS: Lower, Middle, Upper Palaeic Surface.

coincides with the surface, so the maximum trace allowed us to follow low-relief surfaces into more dissected areas where surface remnants may be preserved between fluvial and glacial valleys. After a valley is first incised into a higher landscape, it starts to widen (e.g., *Leopold and Bull*, 1979, Figure 4, Supplement S5) and we identified such places using the minimum height along the profiles (Supplement S6, part 6.2). In summary, we identified the levels of the low-relief surfaces on the map and on the profiles. To ascertain that the interpretation was consistent, we checked that the surfaces on each profile tied at the profile intersections.

4 Relief of the Southern Scandes

The main result of the mapping is the definition of three regional palaeo-surfaces of low relative relief (Figure 8) that make up most of the palaeic relief of the Southern Scandes (Figure 9 and Supplements S1 and S4). Local internal relative relief of the surfaces is <200 m (Figure 6). Where the surfaces are separated by an escarpment, it is typically 200–400 m high (Figure 10). We refer to these surfaces as the Lower Palaeic Surface (LPS), the Middle Palaeic Surface (MPS) and the Upper Palaeic Surface (UPS).

The photographs in Figure 8 illustrate the appearance of the palaeic surfaces (locations in Figure 11; see also Supplement S6). 3D images that simulate oblique aerial photos of the landscape with the interpreted surfaces superimposed are provided, e.g., in Figures 10a, 14c, and Supplement S6 part 6.2.5.

4.1 Lower Palaeic Surface (LPS)

The LPS is an extensive surface in central southern Norway and surrounding the highest areas, particularly

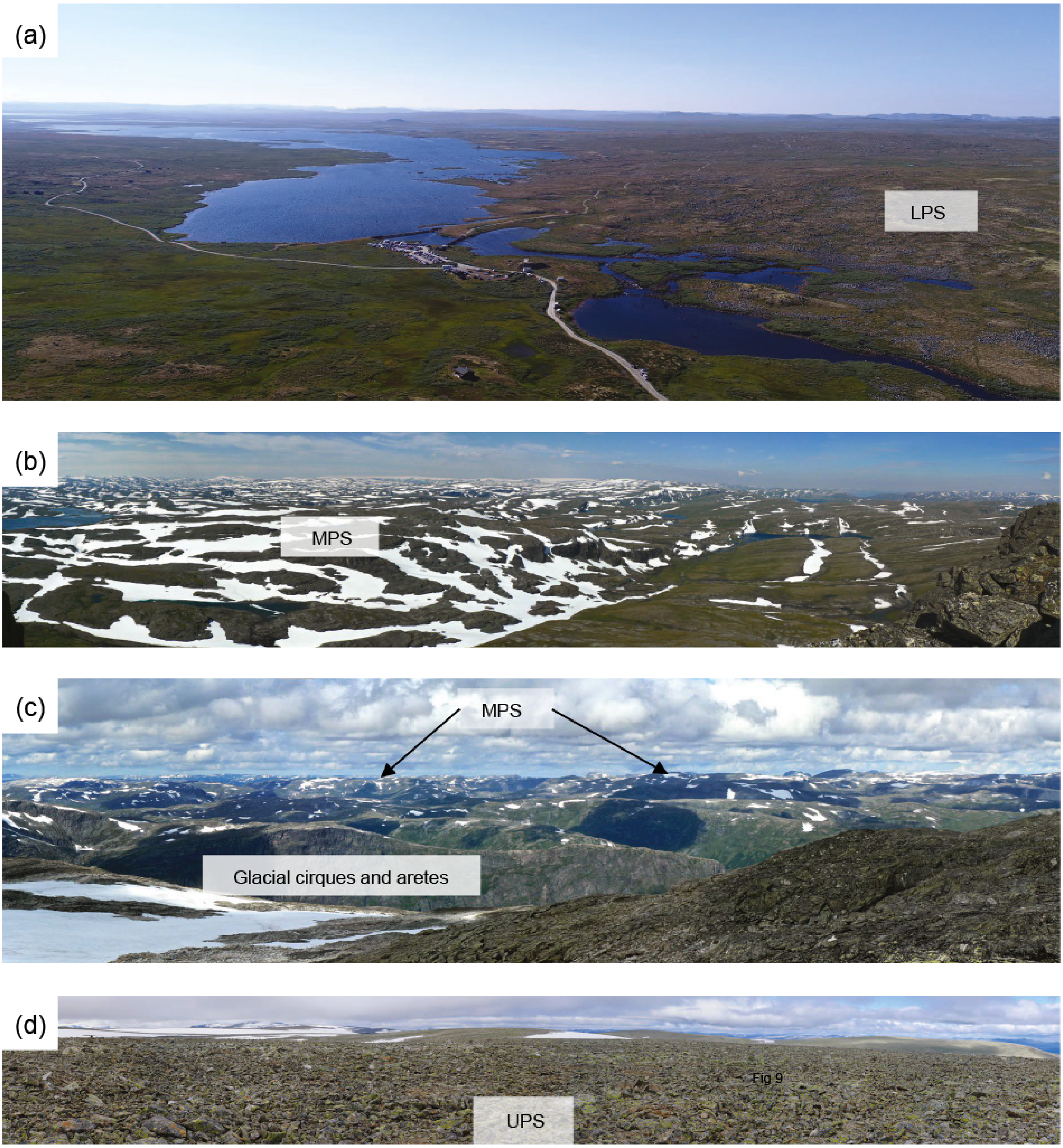


Figure 8 – Photographs of the palaeic surfaces. (**a**) Looking south from the middle of Hardangervidda. The shallow valley containing the river and lakes probably originated as a fluvial valley during formation of the Lower Palaeic Surface, LPS, but has been reshaped somewhat by glacial erosion. The top of the hills in the far background is part of the higher-situated Middle Palaeic Surface, MPS (here highly dissected). (**b**) The MPS looking north from the summit of Hårteigen, western Hardangervidda. The MPS here is cut across Cambro-Silurian meta-sediments (phyllites). It is slightly dissected because of lithology differences within the metasediments. (**c**) Looking NE into Skarvheimen. The low-relief summits are interpreted to be remnants of the MPS; see Supplementary file S7 (c) and (e). The flattish surfaces in the foreground are glacial arêtes and/or the bottoms of glacial cirques. (**d**) Looking west along the summit plateau of Hallingskarvet from near its eastern end showing the remnant of the Upper Palaeic Surface, UPS, preserved here. See Figure 11b for the locations from which these photographs were taken and Figure 1 for place names.

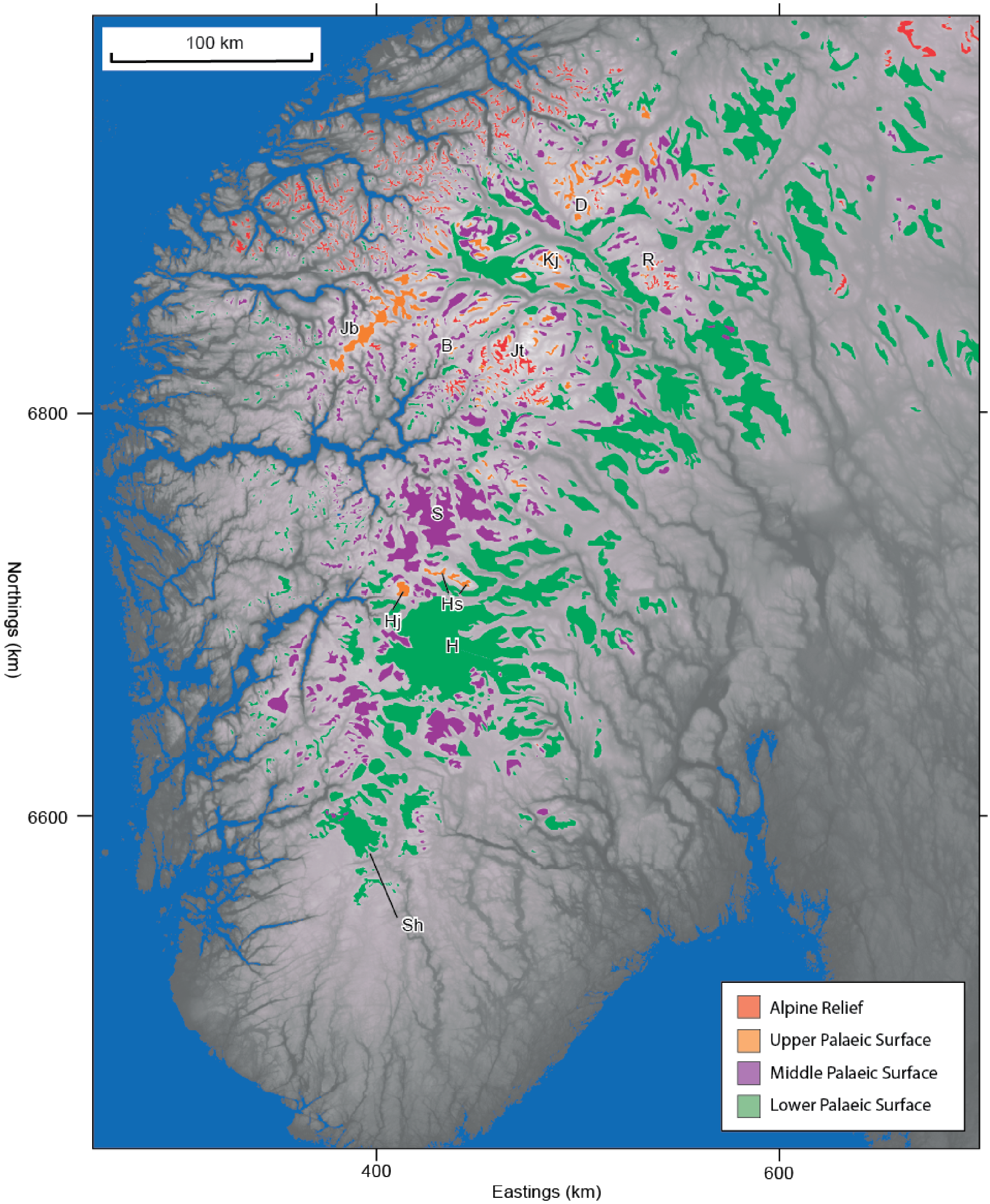


Figure 9 – Remnants of the palaeic surfaces identified in the Southern Scandes. Areas shown as alpine relief are where glacial (cirque) erosion has been sufficiently great to have destroyed all previous landscape features. This applies both to areas higher than the Upper Palaeic Surface (UPS) – Jotunheimen, Dovrefjell and Rondane (Fig. 1a) – and to areas below the level of the UPS and the Middle Palaeic Surface, MPS. These latter areas are found particularly in the NW of the study area, south of the MTFC. Projection: UTM zone 32. B: Breheimen. D: Dovrefjell. H: Hardangervidda. Hj: Hardangerjøkulen. Hs: Hallingskarvet. Jb: Jostedalsbreen. Jt: Jotunheimen. Kj: Kjølen. R: Rondane. S: Skarvheimen. Sh: Setesdalsheiene. LPS: Lower Palaeic Surface.

towards the south, east and north-east (Figure 9). Its mapped extent covers about 90,000 km^2, between northings 6566 and 6990 km (59°N and 63°N); eastings 349 and 701 km (6°E and 13°E) in UTM zone 32 (Supplements S1 and S4). The LPS is found at altitudes between 1000 m and 1400 m (Figure 12a).

The LPS is most extensive on Hardangervidda, where shallow rivers that run across the surface (Figures 6b, 8a) form knickpoints, caused by backward erosion from the deep valleys that incised the surface after it was uplifted (Supplement S6, part 6.2). The LPS can be followed southwards into the area around Setesdalsheiene and northwards east of Skarvheimen to Rondane, then east and north of Jotunheimen to Dovrefjell and further north-east. Small remnants of the LPS are also interpreted in the west, near the coast. North of Jotunheimen, between Kjølen and Dovrefjell, the LPS is developed as gentle benches above and along the deeply incised valleys (e.g. Gudbrandsdalen) that were first incised by rivers and subsequently widened and deepened by glacial erosion (Supplement S6, part 6.2; *Bonow et al.*, 2003). These benches are part of a valley system developed by rivers running from a position west of the present water divide towards the east and south-east (e.g., *Wråk*, 1908; *Bonow et al.*, 2003).

The LPS forms a N–S elongated dome with two main centres where elevations exceed 1300 m; one south-west of Hardangervidda and the other south and east of Sognefjord (Figure 12a). The surface dips west, east and south from the main domes, with a dip of about 1% to the east from the northern dome, east of which the surface is almost flat. Further north, the palaeic landscape has been destroyed by glacial erosion that formed alpine relief.

The cross-section in Figure 12e shows that the LPS is continuous between two areas where *Lidmar-Bergström et al.* (2000) indicated a step between two surfaces; their surfaces IV and V.

4.2 Middle Palaeic Surface (MPS)

The MPS is found in three main areas: (i) The relatively coherent remnant in Skarvheimen (Figures 8c, 9, 10a, 10c), (ii) the large remnants in west and south Hardangervidda (Figures 8b, 9) and (iii) many remnants in the Breheimen, Kjølen and Dovrefjell areas (Figure 9). See also Supplement S6 part 6.3. The MPS is at elevations from 1300 to 1700 m a.s.l. (Fig. 12b). In Breheimen, the MPS is commonly capped by small glaciers S6 part 6. Where the surface is found on Caledonian rocks, its internal topography is locally influenced by differences in lithology. An example is on the phyllites on western Hardangervidda (Figure 8b). The LPS and the MPS are commonly separated from one another by an escarpment (Figure 10).

4.3 Upper Palaeic Surface (UPS)

Only scattered remnants are left of the UPS (Figure 9); for example, the flat summit of Hallingskarvet (Figures 8d, 10a-b; Supplement S6, part 6.4). The most extensive remnants are on Jostedalen and northeast of Jotunheimen in Kjølen and Dovrefjell (Figure 12c; Supplement S6, part 6.2.5). In all areas, the UPS is found between 1600 and 1900 m a.s.l. (Figure 12c).

4.4 The Highest Topography

There are some areas of relief above the UPS, including the highest alpine summits of Jotunheimen, Dovre and Rondane (Figure 9). Their summits are mainly accordant, but no low-relief surfaces can be identified, only alpine landscapes.

4.5 Escarpments Between the Low-relief Surfaces

Winding escarpments and slopes separate the three low-relief surfaces throughout the study area (Figures 6, 10). Some escarpments are at geological boundaries; for example, the upper part of the escarpment of Hallingskarvet consists of resistant metagabbros and separates the UPS above from the MPS and LPS below (Figures 6b, 10a,b). A similar escarpment formed of metagabbro defines the sides of Reineskarvet, but in this case the low-relief summit area consists of MPS with LPS below the escarpment (Figure 10a,c).

Nor does erodibility control the presence of the surfaces. On Hardangervidda, the MPS is found on phyllites, whereas much of the LPS is found on Precambrian gneisses and the boundary between the surfaces consists of an escarpment on the sedimentary rocks (Figure 10d). The phyllites consist of low-grade metasediments and their lowest unit, the Låven Formation, consists of about 30 m of black marine shale, grading upwards into sands and limestones in the uppermost units (*Andresen*, 2021). The presence of this shale layer would make the phyllites easily erodable once any river had cut its way down to it. There is thus no structural control of the escarpments here.

4.6 Relationship Between the Low-relief Surfaces and Geology

Comparison of the extent of the palaeic surfaces and the geology (Figures 3, 9), demonstrates that the three surfaces developed on rocks of different geological provinces; Caledonian metamorphic rocks, Precambrian basement and phyllites. To test if the surfaces were influenced by different geology, we compared our mapped surfaces with geological maps of the area (*Sigmond*, 2002); for example, if a surface follows a resistant rock layer or if an identified step corresponds to a geological boundary (cf. *Fjellanger and Etzelmuller*, 2003; *Green et al.*, 2013). Other influences on the appearance of the surface can be due to differences in resistance to erosion in layered beds. If, for example, a surface cuts across rocks of different lithology, minor differences in altitude between more and less resistant beds are likely to occur. Comparing the maps in Figure 13a,b shows that the surfaces cut across all types of rocks present in southern Norway. Surfaces are also continuous from one type of

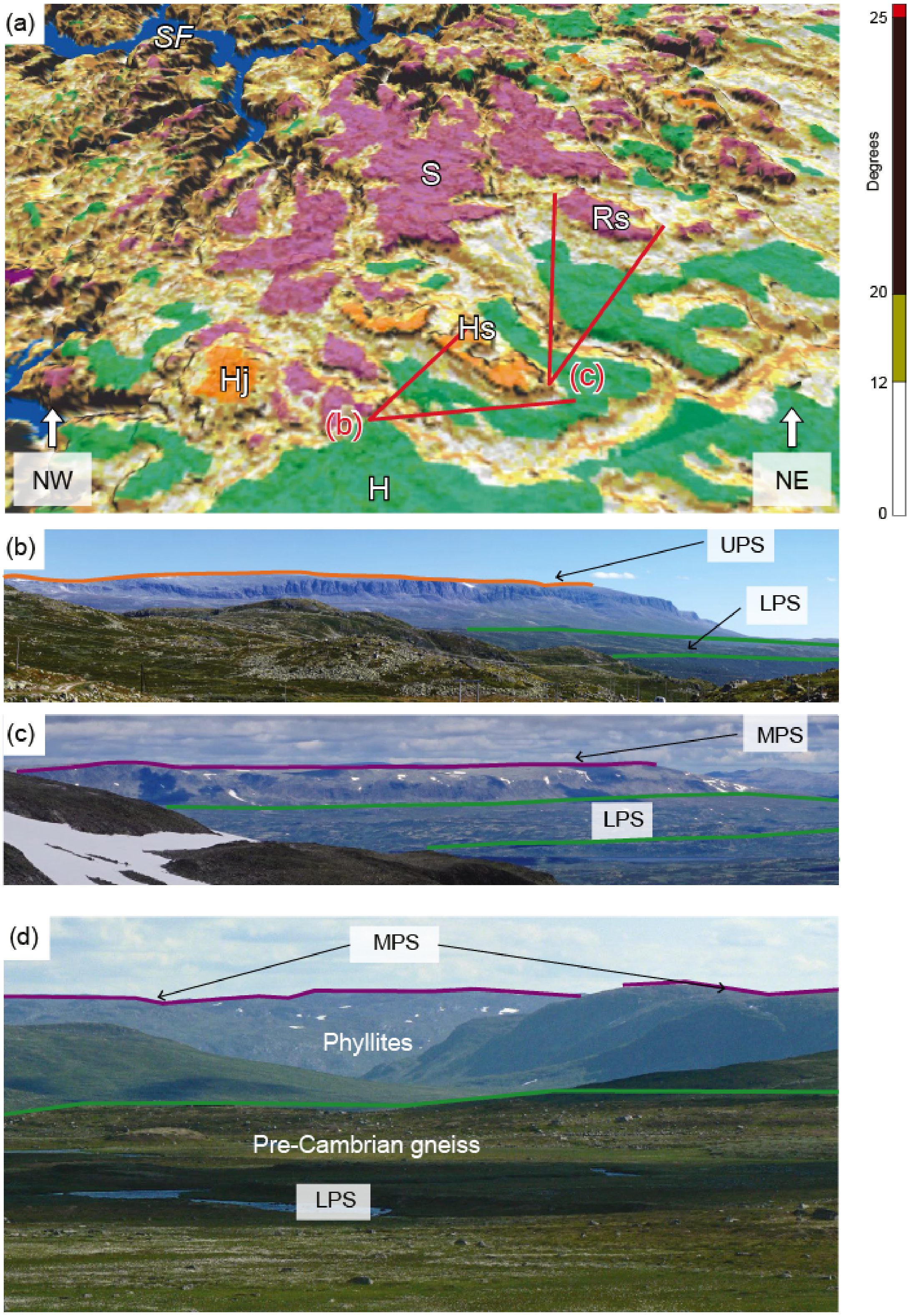


Figure 10 – Escarpments separating the palaeic surfaces. (**a**) 3D image constructed from the DEM with the interpreted surfaces superimposed. See Figure 11a for the location of this view. The palaeic surfaces are shown semi-transparent so that the underlying structure shows through. The dips are colour coded to show the difference between escarpments (dips > 20°), incised surfaces (12° < dips < 20°) and low-angle surfaces. The latter include areas where ice erosion has produced relatively flat surfaces. The scale at the right shows the dip colour-coding. (**b**) Photograph looking NE from Hardangervidda to the escarpment between the LPS and the UPS on the summit of Hallingskarvet (compare with Figure 8d). The slopes on the left-hand-side of the photograph are part of the escarpment between the LPS and the MPS. At this location the latter escarpment is in phyllites. Location on (**a**), labelled '(b)'. (**c**) Photograph looking NE from the east end of Hallingskarvet to the escarpment between the LPS and the MPS on the summit of Reineskarvet. Location on (**a**), labelled '(c)'. (**d**) Photograph on Hardangervidda looking south-east to the escarpment between the LPS on Precambrian gneisses in the foreground and the MPS on the summit of the hills consisting of phyllites. LPS, MPS, UPS: Lower, Middle, Upper Palaeic Surface. Location on Figure 11b.

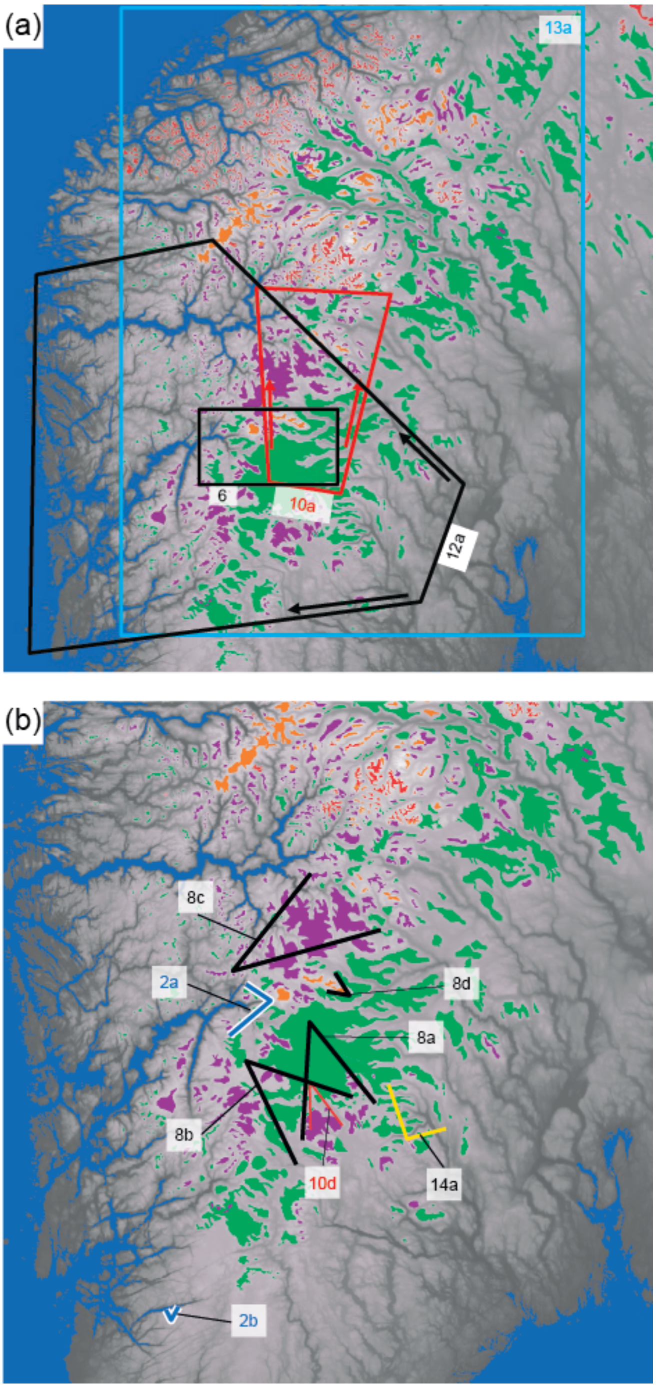


Figure 11 – Location map. (**a**) Field of view on the 3D image in Figures 10 and 12 (arrows show the direction of views) and location of maps in Figures 6 and 13. (**b**) Fields of view of photographs in Figures 2, 8, 10, and 14.

rock to another showing that the geological province is not the primary factor in their formation.

The cross-section in Figure 13c shows that all three surfaces have been eroded at different levels into rocks of one type; Precambrian basement. Their presence at three different levels does not, therefore, depend on the type of rock in the area.

The MPS is present on and around western and southern Hardangervidda (Figures 9 and 13e). In this area it is commonly present on phyllites which (section 5.5) have a much lower resistance to erosion than Precambrian basement. The LPS is, however, present on Precambrian basement on Hardangervidda, but crosses onto the much more easily eroded phyllites farther NE (Fig 13d).

Gabrielsen et al. (2015) argued that the area where basement is exposed on present-day Hardangervidda is the exhumed Base Cambrian Unconformity (BCU). However, *Japsen et al.* (2018) used mapping published by *Schipull* (1974) to show that, in places on western Hardangervidda, the BCU is faulted down in half-grabens and displaced within folds containing phyllites, over which the LPS passes with little disturbance (Figure 13e from e to e'). The LPS in the SE area of Hardangervidda cannot be the BCU either, because of the presence of the Gausta Mountain a short distance to the south of Hardangervidda (Figure 13e from e' to e”). Hardangervidda in this area is at about 1200 m a.s.l., but the summit of Gausta is at 1883 m and consists of Precambrian metasediments (*Köykkä*, 2011). The BCU must therefore once have been above the level of the summit of Gausta, more than 600 m above the level of the LPS.

The LPS is found approximately on the BCU in western Hardangervidda, below it in SE Hardangervidda and above it to the NE of Hardangervidda (Figure 13d,e). We therefore interpret the coincidence of the LPS and the remnants of the BCU on parts of Hardangervidda to be just that, a coincidence, where the present-day erosion levels have just reached the level of the BCU .

To summarise:

(i) the palaeic surfaces are present at three different levels on rocks of the same resistance to erosion (Figure 13c);

(ii) a surface can pass directly from rocks of different resistances to erosion (Figure 13a,b,d);

(iii) a higher surface can be present on rocks of less resistance to erosion than the rocks below a nearby, lower surface (Figure 13d).

Geology is, therefore, *per se* not the primary controlling factor of where these surfaces formed. As we discuss in more detail in section 7, we suggest that the surfaces are peneplains, eroded by rivers graded to a base level of sea level. The three surfaces that occur at different altitudes today were formed at different times by fluvial incision graded to sea level, and the higher surfaces were uplifted before formation of a lower surface.

5 Comparison with other Interpretations of the Palaeic Relief

Our interpretation is comparable to that of *Lidmar-Bergström et al.* (2000) with some differences (Table 1). All of their Level I consists of alpine relief, arêtes and horns in areas where we could find no evidence of any low-relief surfaces. Their Levels II and III are the same as our UPS and MPS. We have amalgamated their Levels IV and V into a single surface,

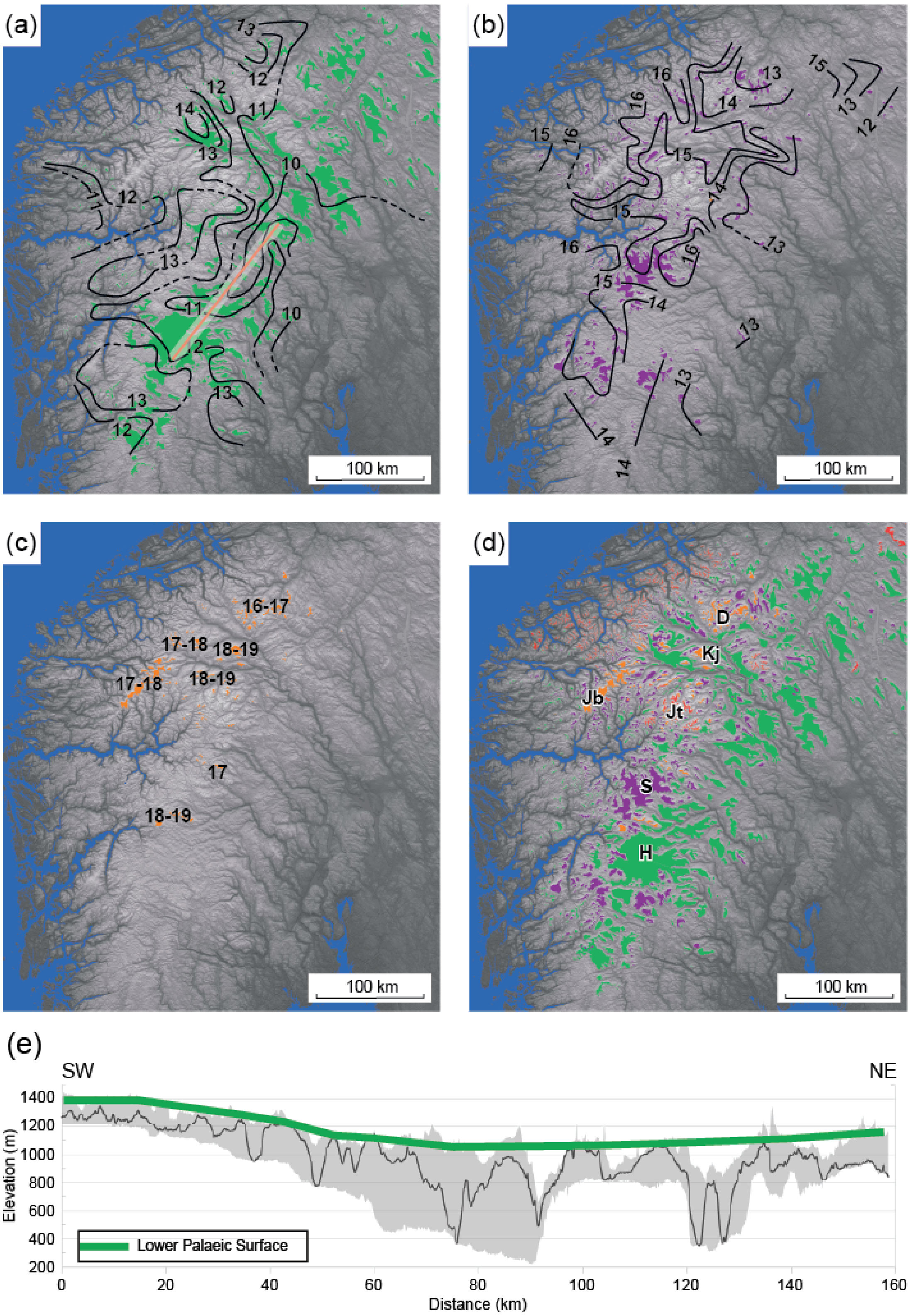
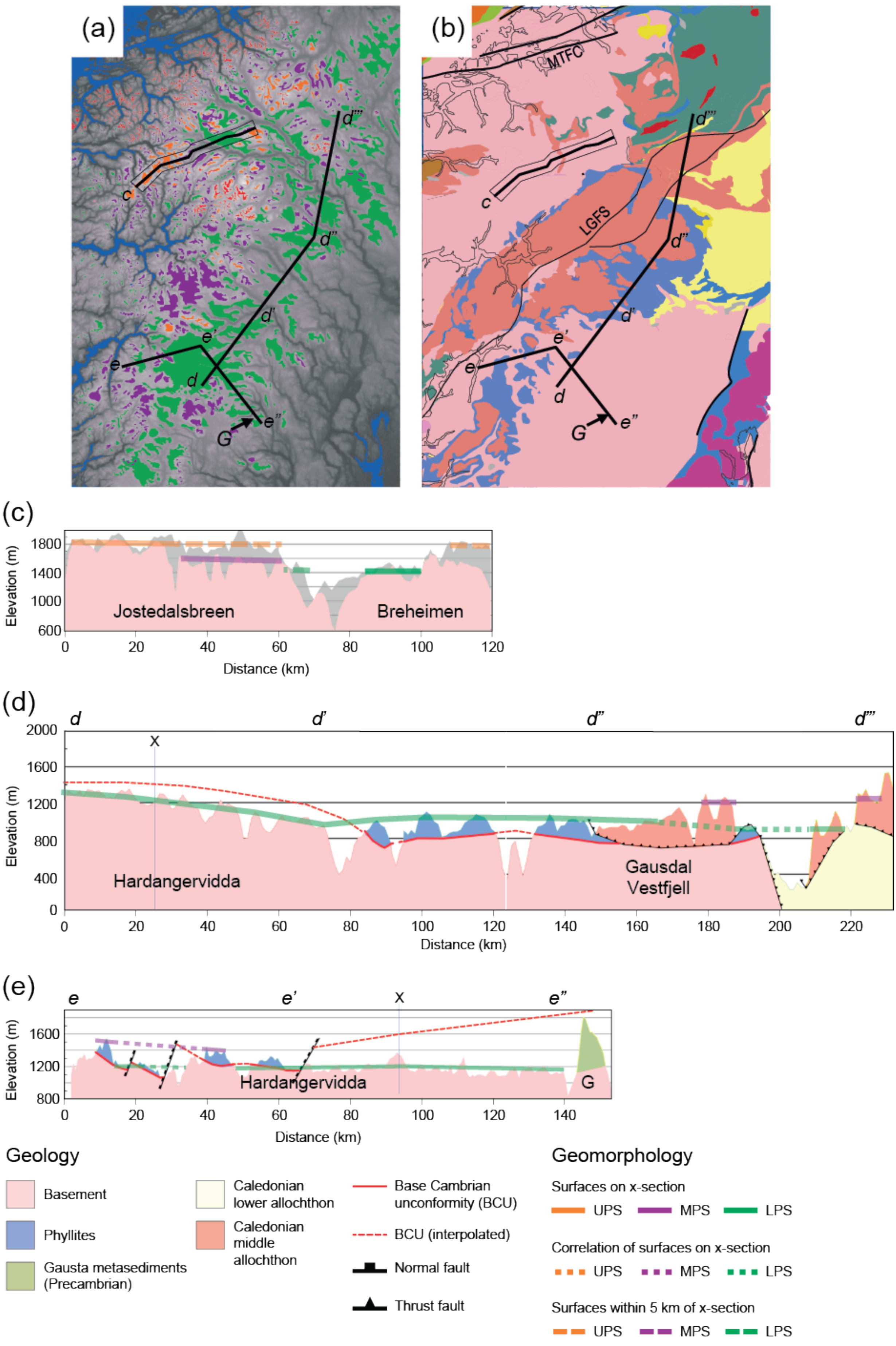


Figure 12 – Elevation maps of the palaeic surfaces. (**a**) Lower Palaeic Surface (LPS). The surface forms two domes in the north and south, two small half domes near the MTFC and a lower-lying area to the north-east. The orange line shows the location of the cross-section in (**e**) and the surrounding grey tone the area within 5 km of the line. (**b**) Middle Palaeic Surface. (**c**) Upper Palaeic Surface. The remnants of this surface are too scattered to draw contours and the ranges of height of the remnants are shown by figures. (**d**) The same map as in Figure 9 showing all three surfaces and the alpine relief. (**e**) Cross-section (vertical exaggeration 20:1) between *Lidmar-Bergström et al.* (2000) Level IV (on the left (SW) side of the section and Level V on the right (NE) of the section showing that the LPS is flexed between these two areas and that they are not separated by an escarpment. The black line shows altitudes along the section and the grey areas show the maximum and minimum altitudes with 5 km each side of the centre line orange line in (**a**) and interpretation of the LPS.



(**Figure 13**, caption on next page)

Figure 13 – Correlation of the palaeic surfaces with geology. (**a**) Map of interpreted peneplains from Figure 9. (**b**) Map of geology from Figure 3. Maps (**a**) and (**b**) are over the same area and their locations are shown on Figures 11a and 3 respectively. (**c**) Cross-section through Jostedalsbreen and Breheimen with a swath showing the maximum altitudes within 5 km of the section (indicated by grey above the trace of the profile). All three palaeic surfaces are present at different levels on the same geological unit; Precambrian basement. (**d**) Cross-section from Hardangervidda through Gausdal Vestfjell. The Lower Palaeic Surface (LPS) is on Precambrian Basement on Hardangervidda (d to d') but is on phyllites (d' to d") and rocks of the Caledonian Orogeny (d" to d'") The Base Cambrian Unconformity (BCU) is below the phyllites from d' to d" and is cut out by the Caledonian nappes from d" to d'". (**e**) Cross-section across Hardangervidda and Gausta mountain (G). The BCU is present below down-faulted and -folded phyllites from e to e', where the Middle Palaeic Surface (MPS) is present above the phyllites and the LPS is at the BCU. The LPS is at the outcrop of Precambrian basement from e' to e", but the BCU must be more than 600 m above Gausta mountain because of the presence of Precambrian sediments there. The BCU must, therefore be well above the LPS from e' to e" See discussion in the text. Place names are indicated on Figure 1.

our LPS, because our detailed analysis showed that this was a single surface that had been warped (Figure 12e). *Bonow et al.* (2003) published an interpretation of surfaces in the Kjølen Mountains, which is consistent with ours.

Fjellanger and Etzelmuller (2003) used a technique of cross-sections similar to ours to identify low-relief surfaces and steps between them. They identified many of the same surfaces as we have on their profiles but did not map them. They concluded that the steps between surfaces seemed to coincide with boundaries between rock massifs of different resistances to erosion. This is certainly true in some cases; e.g. the preservation of the UPS and MPS on the very resistant rocks of Hallingskarvet and Reineskarvet (Figure 10a–d). This is not, however, always the case, for example in the Hardangervidda area where some escarpments are formed in low-grade phyllites (Figure 10d).

Etzelmüller et al. (2007) published an interpretation of the topography of southern and northernmost Norway using a statistical analysis of the topography (based on averaging the topography into cells of 7 km diameter). A comparison of our interpretation with theirs shows a number of major differences. Our approach has distinguished many planation surface remnants, especially of the MPS and UPS that are smaller than the 7-km window used by *Etzelmüller et al.* (2007). The 7-km window has clumped our MPS, UPS surfaces together with the higher alpine topography into their 'Higher mountain plateaus (Table lands, "vidde")' (see Supplement S7 for details).

Bernard et al. (2025) encountered problems similar to those of *Etzelmüller et al.* (2007) regarding the identification of the separate levels of the palaeic relief. They used a numerical, glacial landscape-evolution model to quantify the effect of Pliocene-Quaternary glaciations on the topography of a mountain range. Examination of the Google Earth image in their figure 1a (the only example from Norway), demonstrates that what these authors identified as low-relief surfaces are a ridge eroded between two converging ice streams (left-hand example) and a cirque (right-hand example).

In contrast to our definition that low-relief surfaces dip less than 6.5°, *Bernard et al.* (2025) used a limit of 20° dip. While the surfaces mapped in this study are included in the study of *Bernard et al.* (2025), they also included what we interpret as slopes and escarpments between surfaces and they thereby miss the discrete steps between the surfaces, concluding that the low-relief surfaces are distributed across elevations.

Their numerical modelling thus failed to show that the surfaces of the palaeic relief are separated by well-defined escarpments (Figure 10) and that each of the surfaces can be traced over long distances (Figure 7), not least the LPS that extends as a coherent surface across 90,000 km^2 incised by valleys (Figures 9, 14). Their technique did not allow *Bernard et al.* (2025) to distinguish between surfaces at different elevations; the three palaeic surfaces that we have defined (compare their figure 10k with Figure 9). Finally, their technique did not allow them to distinguish between the palaeic surfaces and slopes incised by rivers or ice.

Several studies have investigated whether glacial processes were responsible for the formation of the elevated, low-relief plateau regions in the Southern Scandes. One example is the computer experiments of *Egholm et al.* (2017). However, these computer models showed that long-term glacial erosion could produce 'interfjord plateaus', less than 30 km wide where ice was flowing away from the central ice sheet. The palaeic relief extends across hundreds of kilometres in the central areas of southern Norway and only small portions of the palaeic surfaces are preserved on the ridges between deep fjords and valleys. The modelling by *Egholm et al.* (2017) is, therefore, not relevant to understanding the formation of the palaeic relief surfaces.

6 Evidence for When and How the Palaeic Surfaces Formed

Observations from the sedimentary basins surrounding southern Norway (e.g., *Evans et al.*, 2003; *Peron-Pinvidic et al.*, 2017) contain information about the development of the Southern Scandes. We constrain the timing for the formation of the palaeo-surfaces by the relative denudation chronology defined by our analysis, evidence from the surrounding sedimentary basins of periods of sand deposition resulting from erosion of the Southern Scandes and correlation of them with episodes of cooling and exhumation from AFTA data (*Green et al.*, 2022; *Japsen et al.*, 2024).

Two of the three palaeic relief surfaces cut off (erode) the Jurassic surface on the flanks of the Southern Scandes

Table 1 – Comparison of surfaces interpreted in this paper with those reported in other papers.

This paper	*Lidmar-Bergström et al.* (2000)	*Bonow et al.* (2003)	*Etzelmüller et al.* (2007)
Surfaces based on actual topography	Surfaces based on summit surfaces	Surfaces based on actual topography	Automatic regional classification of topography
High alpine relief (>2000 m a.s.l.)	Level 1		High palaeic mountains with glacial incisions, most moderate slopes
Upper Palaeic Surface	Level 2	A	
Middle Palaeic Surface	Level 3	B	
Lower Palaeic Surface	Level 4	C	Higher mountain plateaus (Tablelands, "vidda")
	Level 5		Lower mountain plateaus (Tablelands, "vidda")

(Figure 7a) and the third probably also did as it is sub-parallel to the others Figure 12). This implies that they are all younger than Jurassic, and we can, therefore, focus our attention for geological evidence for how the palaeic surfaces formed in times younger than that.

6.1 Turonian Fan Systems off Mid-Norway

Sømme and Jackson (2013) documented the emplacement of sand-rich submarine fan systems offshore west Norway during a 3 Myr period in the Turonian–Coniacian above an intra-Turonian unconformity (c. 90 Ma). They suggested that the unconformity and the associated canyons are linked to the Cenomanian–Turonian extensional tectonic event observed along the Norwegian margin (e.g., *Lundin and Doré*, 1997). The systems were fed by sediments that were routed through submarine canyons incised into the basin margin, sourced by drainage catchments that extended more than 100 km inland from the palaeo-shoreline. Consequently, the authors suggested that the distribution of fan systems along the margin reflects the proximity to large river systems. The Turonian–Coniacian deposition overlaps with the onset of earliest Late Cretaceous exhumation (beginning between 95 and 90 Ma) that affected Fennoscandia and Greenland (*Green et al.*, 2022; *Japsen et al.*, 2024).

6.2 Paleocene Sedimentation West of Norway

Fan sedimentation west of Norway started in the Maastrichtian at 68 Ma and the rate of fan sedimentation increased and continued through the Paleocene (*Sømme et al.*, 2019). The fans developed from rivers originating in the present-day Norwegian mainland, flowing approximately along the present-day Nordfjorden, Sognefjorden and Hardangerfjorden (Figure 1). These rivers would have flowed over and eroded Jurassic–Palaeogene sediments that covered the west flank of Norway at that time (*Japsen et al.*, 2018), consistent with the content of reworked Cretaceous sediments in these wedges (*Sømme et al.*, 2019). The latter authors also showed that the uplift needed to produce these sediments is of the order of several hundred metres. The Paleocene tectonic event overlaps with the onset of Maastrichtian–Paleocene cooling resolved in AFTA data in an area south of the MTFC (*Green et al.*, 2022), that *Japsen et al.* (2024) argued corresponds to regional, Paleocene exhumation beginning at c. 62 Ma.

6.3 Early Miocene Progradation of Deltas into the Danish Basin

Prior to the Miocene, sea covered all of what is now Denmark for millions of years, but in the early Miocene at c. 22 Ma, the sea became filled with deltaic sediments transported by braided rivers originating in the Scandinavian hinterland (*Rasmussen et al.*, 2010; *Rasmussen*, 2014; *Japsen et al.*, 2018). Heavy mineral assemblages in the delta show that the Norwegian source area was the south and east of Norway, consistent with the areas where we map the LPS (*Olivarius et al.*, 2014). The rivers flowed mostly towards the east and south, shown by the presence of gentle pre-glacial palaeo-valley systems and valley benches now at high elevations (Figures 9, 14c; Supplement S6, part 6.2) These rivers originate today west of the current water-divide because of river capture during the Quaternary (*Reusch*, 1905; *Wråk*, 1908; *Ahlmann*, 1919; *Bonow et al.*, 2003). *Śliwińska et al.* (2024) provided further documentation for input of fluvial sediments to the Danish Basin from the north and north-east starting at 23 Ma and showed that the input ceased at 15 Ma. The date of onset of sedimentation corresponds closely to the onset of exhumation defined by AFTA that began between 21 and 23 Ma and affected all of Fennoscandia as well as the offshore region west of southern Norway (*Japsen et al.*, 2018; *Green et al.*, 2022).

6.4 Ages of the Palaeic Surfaces

The three palaeic surfaces are all younger than Jurassic (Figure 7a). We also cite evidence that shows that there was substantial fluvial erosion of southern Norway in the Turonian–Coniacian, Paleocene and early Miocene, that overlaps with the onset of significant episodes of exhumation defined by AFTA. We therefore interpret the palaeic surfaces as having been formed by removal of these sediments by rivers. River erosion incises landscapes until the erosion level reaches a base level, below which the rivers cannot erode and forms peneplains. Widening of valleys by erosion of the slopes is the primary agent for erosion followed by removal of the erosional products by the river systems (Supplement S5; e.g.; *King*, 1967; *Leopold and Bull*, 1979; *Ritter et al.*, 2001). The very flat nature of the palaeic surfaces shows that the fluvial erosion that formed them was graded to former base levels and they are therefore peneplains. As the study area was adjacent to the ocean at these times (*Rasmussen et al.*, 2010; *Sømme and Jackson*, 2013; *Sømme et al.*, 2019), the most likely candidate for base level was sea level.

Formation of stacked peneplains happens successively, by an older peneplain being uplifted and incised and after some time, a younger peneplain forming below it (see Supplement S5). This means that the younger peneplains in the stack are the lower. The UPS formed as a coherent surface by erosion into older higher levels; the areas preserved as e.g. the Jotunheimen. After uplift of the UPS, the MPS formed, initially along the precursor valleys to the later LPS and parts of the UPS were destroyed in this process. After another uplift, parts of the MPS were destroyed by backward erosion along those same valleys as the LPS formed by grading to a new base level below the uplifted MPS.

We conclude that the UPS formed as a result of Late Cretaceous uplift (starting between 90 and 95 Ma), the MPS formed in the Maastrichtian and Paleocene (starting at c. 68 Ma; and we will refer to it as a Paleocene surface) and the LPS formed during the Miocene (starting at c. 22 Ma).

6.5 Pre-glacial River Incision and Uplift of the Palaeic Relief

The initial incision of the Rjukan Valley, a deep valley incising SE Hardangervidda, was by rivers (Figure 14). Extrapolation of the uppermost valley sides show two V-shaped valleys some 350 to 500 m deep below the level of the LPS, which were later deepened by glacial erosion. *Bonow et al.* (2003) reported similar features in Gudbrandsdalen. Incision of rivers in this way indicates that the Southern Scandes were uplifted after formation of the LPS but before the onset of glaciation (*Rudberg*, 1988; *Lidmar-Bergström et al.*, 2000; *Bonow et al.*, 2003).

Offshore NW 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). Regional AFTA data (including data from deep wells in the Danish Basin and in Finland) provide evidence for a phase of Pliocene exhumation beginning c. 5 Ma (*Japsen et al.*, 2024). *Japsen et al.* (2018) summarised these and other observations and suggested that uplift of Hardangervidda – and thus of the palaeic relief – began in the early Pliocene, an interpretation that we adopt in this study.

The present-day configuration of the palaeic relief relative to the Jurassic surface on the flanks of the Southern Scandes is illustrated by the conceptual diagram in Figure 4, where the UPS, MPS and LPS correspond to surfaces (I), (II) and (III). Table 2 provides a summary of the observations that we used to date the formation of the palaeic surfaces.

7 Preservation of the palaeic surfaces

7.1 Preservation of the Jurassic and Palaeic Surfaces

Green et al. (2022) showed that the AFTA data from across Fennoscandia defined a history of repeated episodes of burial and exhumation. They argued that, even if the peneplains defined across Scandinavia (e.g., *Lidmar-Bergström et al.*, 2013) are limited in their extent today, the AFTA data show that the exhumation episodes that led to their creation are widespread. The intervening episodes of subsidence resulted in re-burial of the peneplains below sedimentary covers and thus contributed to their preservation.

Three phases of subsidence and burial affected the study area in the interval between mid-Jurassic and early Miocene exhumation:

(i) Late Jurassic – Early Cretaceous post-rift subsidence. Jurassic sediments are present offshore west of southern Norway and in scattered remnants onshore (Section 2.3). The Upper Jurassic, Cretaceous and younger sediments offshore today provide a protective cover preserving the Jurassic basement surface (Figure 5). The vitrinite reflectance and AFTA data from the Jurassic outliers onshore and adjacent basement show that the Jurassic surface on the flanks of the Southern Scandes was buried below a thick, protective cover of Upper Jurassic to Oligocene sediments prior the onset of the Miocene exhumation (Section 2.3). The AFTA data from southern Norway also provide palaeotemperatures that show that the region was buried by Upper Jurassic and Lower Cretaceous sediments prior to the episode of earliest Late Cretaceous cooling (*Green et al.*, 2022).

(ii) *Sømme et al.* (2019) showed that the relief of the Southern Scandes was low during the Late Cretaceous, in agreement with the interpretation presented here, that the UPS had been graded to sea level. A shallow sea transgressed the low-lying UPS during the high global sea level and sediment was deposited across much of the Southern Scandes, explaining the extremely low siliciclastic input to the North Sea chalk basin (*Jarsve et al.*, 2014). The former presence of Upper Cretaceous sediments across parts of southern Norway is indicated by the common occurrences of large, rounded clasts of flint, quartz and quartzite in the lower Miocene succession of the Danish Basin (*Rasmussen and Dybkjær*, 2020) and reworked Cretaceous microfossils in the Paleocene sands offshore southern west Norway (*Sømme et al.*, 2019).

(iii) Eocene–Oligocene subsidence and burial after the onset of sea-floor spreading in the NE Atlantic in the early Eocene is documented in East Greenland (*Japsen et al.*, 2021) and there is no reason to assume that it wouldn't have occurred in Norway, too. Extrapolation of early Miocene paleotemperatures shows that, at the onset of the early Miocene exhumation, the UPS and

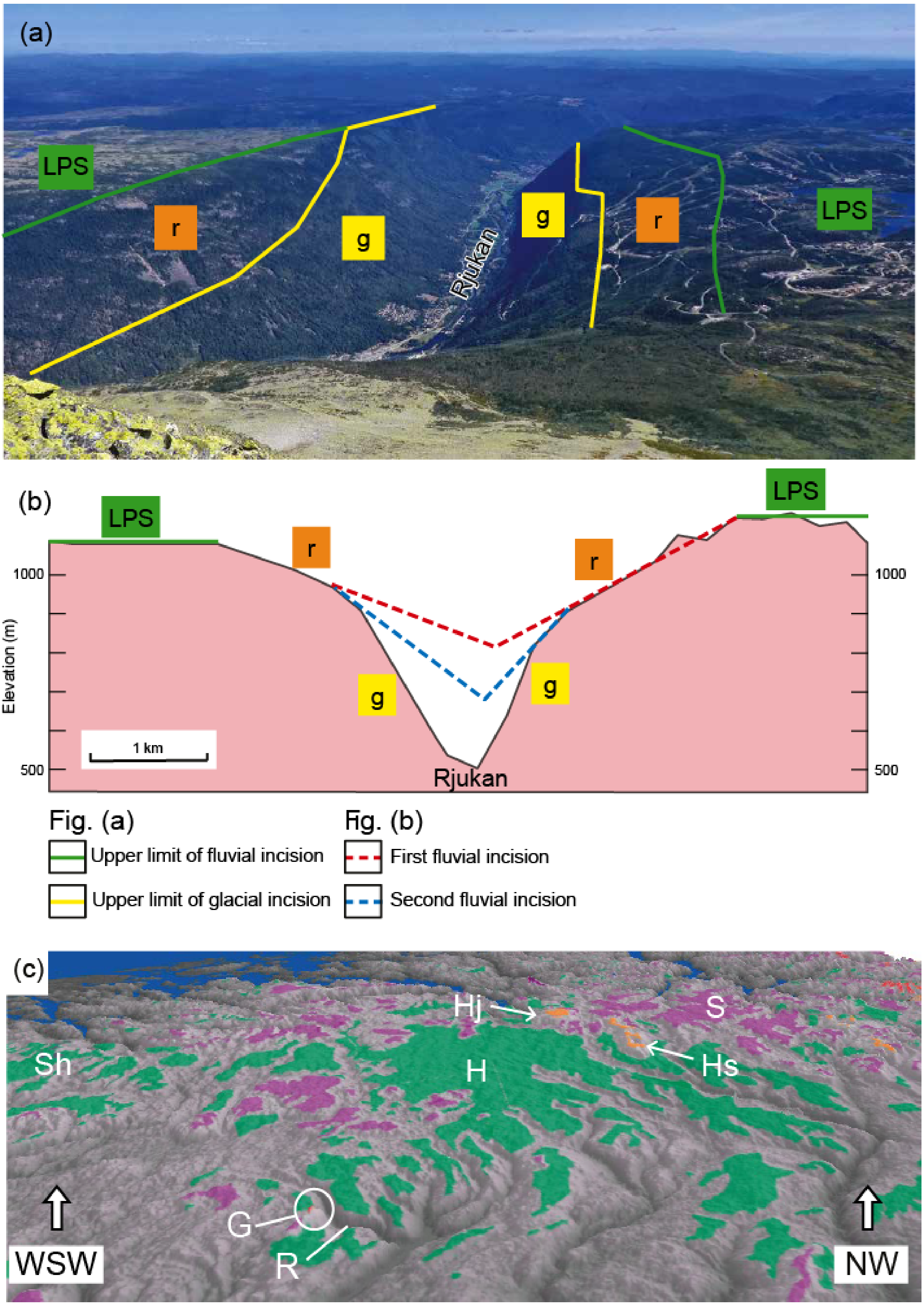


Figure 14 – Incision of the Lower Palaeic Surface (LPS) by a river valley that is later deepened by glacial erosion. (**a**) Photograph looking north-east into the Rjukan Valley from the summit of Gaustafjell (location shown on Figure 11b). Remnants of the LPS are visible on both sides of the valley (that on the left is Hardangervidda). The upper valley sides ('r') slope less than the lower valley sides ('g'). (**b**) Cross section of the Rjukan valley (vertical exaggeration 3.4:1). Two extensions of the upper valley sides – red and blue dotted lines; not separated in (**a**) – meet in V's at ca. 700 and 850 m a.s.l. each forming a cross-section typical of a river valley. The presence of two heights for the bottoms of the river valleys indicates a change in the level to which the river was grading. The river valleys were later deepened by a glacier. (**c**) 3D image constructed from the DEM with the interpreted surfaces superimposed. See Figure 11a for the location of this view. The palaeic surfaces are shown semi-transparent, so that the underlying structure shows through. The eastern flanks of both Hardangervidda (H) and Skarvheimen (S) are incised by deep river valleys that were later modified by glacial erosion. Gaustafjell (G) rises above the Rjukan Valley (R) as alpine relief. Hj: Hardangerjøkull. Hs: Hallingskarvet. Jt: Jotunheimen. Sh: Setesdalsheiene.

Table 2 – Evidence for phases of uplift and erosion and the ages of the surfaces / Denudation chronology.

Surfaces defined in this study	Estimated timing for the formation of the surfaces	Onset of exhumation*	Relative denudation chronology	Observations from the stratigraphic record
The Jurassic surface on the slopes of the Southern Scandes (SS)	Mid-Jurassic	180–170 Ma Middle Jurassic	The formation of a bedrock surface with hilly relief and fracture valleys occurred by chemical weathering in fractures during warm, humid conditions in the Mesozoic (LB2013). The surface was transgressed in the Late Jurassic (F1997; J2018). The hilly bedrock surface is everywhere located below the plains of the palaeic relief (LB2013).	The slope dips from the palaeic relief to the coast and to 1.5 km below sea level west of Norway, where it is covered by Upper Jurassic and younger sediments (Figure 4; J2018).
Upper Palaeic Surface (UPS)	Late Cretaceous	95–90 Ma Earliest Late Cretaceous	The UPS is sub-parallel to the LPS which truncates the Jurassic surface on the slopes of the SS. The UPS is therefore post-Jurassic	Submarine fan systems west of Norway above an intra-Turonian unconformity (c. 90 Ma; S2013b). Movement on the MTCF, onset of STZ inversion (J2016; W2023).
Middle Palaeic Surface (MPS)	Paleocene	c. 62 Ma Mid-Paleocene	The MPS was incised below the UPS. The LPS is therefore post-Jurassic	Fan sedimentation started west of Norway at c. 68 Ma, and the rate of fan sedimentation increased and continued through the Paleocene (S2019).
Lower Palaeic Surface (LPS)	Miocene	c. 22 Ma Early Miocene	The LPS was incised below the MPS and truncates the Jurassic surface on the slopes of the SS. The LPS is therefore post-Jurassic.	Braided rivers originating in the Scandinavian hinterland transported deltaic sediments that reached the Danish Basin in the early Miocene (R2010; O2014).
Incision of valleys. Re-exposure of the Jurassic surface	Pliocene	c. 5 Ma Early Pliocene	The hilly bedrock surface on the flanks of the SS was preserved below a protective cover until its re-exposure following relatively recent uplift, that also led to incision of large fluvial valley systems (LB2013). The uplift began in the Pliocene and initiated the rise of the palaeic relief to its present elevation (J2018).	A regional intra-Neogene unconformity offshore NW Europe developed in response to pre-glacial uplift and tilting of the continental margin (S2005). Initial incision of valleys below the LPS by rivers (Figure 14; S1974). Re-exposure of the hilly Jurassic surface on the slopes of the SS (Figure 2b; LB2013)
Recent landscapes	Quaternary		Glacial incision and removal of rocks were intensified during the Quaternary (H2013; F2013).	Transformation of fluvial valleys to glacial valleys and fjords, while leaving the high-lying plateaus relatively unaffected by erosion.

* Based on AFTA data from Greenland, Fennoscandia, Svalbard and the Barents Sea, Danish Basin (*Green et al.*, 2022; *Japsen et al.*, 2024).
F1997: *Fossen et al.*, 1997. F2013: *Fredin et al.*, 2013; H2013: *Hall and Kleman*, 2014; J2016: *Japsen et al.*, 2016. J2018: *Japsen et al.*, 2018.
LB2013: *Lidmar-Bergström et al.*, 2013. O2014: Olivarius et al., 2014. R2010: *Rasmussen et al.*, 2010. S1974: *Schipull*, 1974.
S2013b: *Sømme et al.*, 2013. S2019: *Sømme et al.*, 2019. S2005: *Stoker et al.*, 2005. STZ: Sorgenfrei-Tornquist Zone. W2023: *Watts et al.*, 2023.

the MPS were buried and there was little or no cover above the summits of Jotunheimen (*Green et al.*, 2022).

These sedimentary covers were removed partially during the three phases of exhumation that led to the formation of the UPS, MPS and LPS and, in the present-day region offshore west of southern Norway, sedimentary units that accumulated during these subsidence episodes are all truncated towards the coast (*Jensen and Schmidt*, 1992; *Japsen et al.*, 2012a, their Figure 2).

It thus seems likely that sedimentary covers reached far over the present-day onshore region and contributed to the preservation of not only the Jurassic surface but also of the UPS and the MPS.

7.2 Preservation of the Palaeic Surfaces During the Quaternary

Glaciers in the Quaternary widened and deepened the Pliocene fluvial valleys, reshaping them to glacial valleys and fjords (*Rudberg*, 1988; *Stroeven et al.*, 2002; *Kleman*, 2008; *Lloyd et al.*, 2023). In detail, glacial erosion has modified all landscapes in Norway; striae and glacial drift, for example, can be observed at most locations (e.g., *Thoresen*, 1991), so the surfaces of the peneplains have been modified by minor erosion by glaciers, and also by periglacial processes during interstadial times (*Marr et al.*, 2018). The main features of the peneplains, however, including steps and escarpments, have been maintained because the bed of the ice at high elevation was frozen to its underlying surface and was therefore mostly non-erosive (e.g., *Kleman*, 1994, 2008; *Hättestrand and Stroeven*, 2002; *Kleman and Glasser*, 2007; *Hall and Kleman*, 2014; *Marr et al.*, 2018). This observation is supported by the presence of extensive sub-glacial dendritic river valley patterns beneath both the Greenland and Antarctic ice sheets (*Sugden and Jamieson*, 2018; *Jess et al.*, 2020; *Paxman et al.*, 2021, 2024).

8 Mechanisms of Uplift to Form the Surfaces

The mechanisms that led to the uplift and formation of the palaeic relief and to the intervening phases of subsidence, are not well understood. Flexural isostatic response to the incision of the deep valleys and fjords contributed some 800 m of rock uplift and 500 m of topographic uplift to the present-day overall relief, which is not enough to account for all of the uplift (*Medvedev and Hartz*, 2015). The 200–400 m separations in altitude between the peneplains are too great to be the direct result of eustatic sea level changes (e.g., *Miller et al.*, 2005), so at least part of the driving mechanisms for the uplift must be tectonic.

It has been argued that the topography of the Scandinavian mountains remained high since the Caledonian orogeny (*Nielsen et al.*, 2009; *Pedersen et al.*, 2016; *Balling et al.*, 2026). In particular, *Pedersen et al.* (2016) considered the low-relief landscape in western Scandinavia to be a 'remnant of Caledonian topography'. The proponents of this hypothesis ignore the evidence that the Caledonian mountains collapsed during the Devonian (e.g., *Fossen*, 2000, and references therein) and have also chosen not to consider the configuration of the palaeic relief in stepped sequences that truncate the tilted Jurassic surface.

Redfield et al. (2005a) concluded that "… the Southern Scandes 'dome' is revealed as a faulted, asymmetric reactivated rift shoulder …". We can test this interpretation by calculating the size of footwall uplift produced by a fault similar to the MTFC, assuming that it was caused by flexure of a crust with an elastic thickness of 30 km (*Watts*, 2001, their Figure 8.30). The width of such a flexed footwall uplift is, however, less than 100 km, much less than the approximately 400 km of the South Scandes dome (Figure 72 of *Green et al.*, 2013). Footwall uplift should not persist after rifting but should subside post-rift to form a so-called "steers-head" geometry of the basin margin (White and McKenzie, 1988). Subsidence and burial of the present-day landscape to the north of the MTFC is documented by vitrinite reflectance values in Jurassic coal that correspond to burial beneath 2–2.5 km of post-Jurassic sediments (*Weisz*, 1992; *Bøe et al.*, 2010; *Olesen et al.*, 2023); a result confirmed by AFTA data (*Green et al.*, 2022).

8.1 The Hilly Jurassic Surface on the Flanks of the Southern Scandes

We suggest that the uplift and erosion that caused formation of the Jurassic surface on the slopes of the Southern Scandes were related to the same mechanism that gave rise to the mid-Jurassic mid-Cimmerian Unconformity (MCU) in the North Sea. *Underhill and Partington* (1993) related the MCU to the late Toarcian (c. 175 Ma) rise of a small plume under the central North Sea, associated with volcanism. However, the doming in the North Sea was part of a much larger area affected by mid-Jurassic exhumation, including Scandinavia and East Greenland (see figure 4E of *Japsen et al.*, 2024), representing the final phase of the break-up of Pangaea (*Veevers*, 2013; *Japsen et al.*, 2016).

8.2 The Late Cretaceous UPS

The MTCF (and possibly the LGFS) are marginal faults of the Early Cretaceous basins that extend all the way from offshore northern Norway to the Rockall Trough west of Ireland (*Doré et al.*, 1999). One possible hypothesis for the formation of the UPS is that the surface developed as a consequence of earliest Cretaceous footwall uplift from these fault systems (Figures 1, 3). Footwall uplift is, however, confined to less than 100 km of the faults (see Figure 72 and associated discussion in *Green et al.*, 2013), and the 150 km extent of the UPS between MTFC and LGFS (Fig. 12c) is thus too large to have been caused by footwall uplift from the MTFC.

This extension took place also some 30 Myr earlier than the onset of the early Late Cretaceous exhumation event recorded by AFTA, that affected East Greenland, Svalbard and Fennoscandia, an area far larger than that of the remnants of the UPS preserved today (see Figure 4D of *Japsen et al.*, 2024). Major unconformities of similar age occur in these areas and a deeply weathered, mid-Cretaceous peneplain formed over large parts of Sweden and Finland as a result of the exhumation (see references cited by *Japsen et al.*, 2024). There is also a "gentle to angular unconformity" of Cenomanian age in the basins NW of Norway (*Doré et al.*, 1999) that could have been caused in a similar way to the compression event that caused the Miocene folding west of Norway (*Lundin and Doré*, 2002). Inversion of the Sorgenfrei-Tornquist Zone in southern Scandinavia also shows the presence of compression around 100 Ma (*Japsen et al.*, 2016).

We therefore suggest that the UPS was formed after crustal-scale folding that involved bending of the mid-Jurassic peneplain in Norway (*Japsen et al.*, 2024). The driving force may be the same as that which caused movement of the Adria plate northwards relative to the European plate, initiating subduction of the intervening oceanic crust and causing basin inversion and thrusting in central Europe (*Kley and Voigt*, 2008; *Pfiffner*, 2005).

Subsidence and sedimentation after the early Late Cretaceous uplift event could have been a continuation of "steers-head" subsidence after the early Cretaceous rifting and foot-wall uplift on the MTFC and LGFS (*White and McKenzie*, 1988).

8.3 The Paleocene MPS

The primary, direct evidence for Paleocene uplift is the fan sedimentation west of Norway, which was derived from the Norwegian hinterland, reaching the fans via rivers flowing west (*Sømme et al.*, 2019). *Sømme et al.* (2019) showed that fan sedimentation started at 68 Ma, coincident with the onset of doming above the Iceland plume rising below central Greenland (*Japsen et al.*, 2023). The dome was ca. 2000 km in diameter; a size consistent with the calculations of *Campbell* (2007) and with the area affected by the Maastrichtian rise of the Iceland plume (*Japsen et al.*, 2023). Southern Norway was thus within the eastern side of this rising dome.

Sedimentation rates within the fans increased from the Maastrichtian through the Paleocene, being derived from a landscape that increased in altitude to an estimated maximum of 350 m; close to the separation between the MPS and UPS (*Sømme et al.*, 2019). Fan sedimentation ceased at the end of the Paleocene at approximately the same time as the onset of sea-floor spreading between Norway and Greenland at c. 55 Ma (*Gaina et al.*, 2017), presumably due to the collapse of the dome as magma erupted at the surface.

8.4 The Miocene LPS

The early Miocene uplift and erosion that affected Fennoscandia – but not Greenland (see Figure 4F of *Japsen et al.*, 2024) – led to the formation of the LPS in southern Norway and an equivalent peneplain in southern Sweden (*Japsen et al.*, 2016, 2018). We consider it likely that the exhumation was related to compressional intra-plate stress on the Eurasian plate. We note that there was a hard collision between the Europe and Adria plates at this time (*Pfiffner*, 2005) and Himalayan tectonics changed from continental subduction to a hard collision between India and Asia (*van Hinsbergen et al.*, 2012).

8.5 The Final, Post-Miocene Formation of Modern Topography

The final uplift, that started in the early Pliocene (Japsen et al., 2024), raised the UPS, MPS and the LPS to their present elevations, led to re-exposure of the hilly relief of the mid-Jurassic surface below the LPS and to formation of the modern topography by incision of valleys and fjords below the LPS. Flexed isostatic uplift contributed to the present-day overall relief (*Medvedev and Hartz*, 2015), but not enough to account for all of the uplift. The amount of flexed uplift may need to be increased to take account of the removal of sediment that was present on the flanks of southern Norway prior to 5 Ma.

Early Pliocene uplift raised the conjugate margins of the NE Atlantic to maxima where Greenland is closest to Iceland (black numbers in Figure 4F of *Japsen et al.*, 2024). This indicates that dynamic support from the Iceland plume contributed to the early Pliocene uplift due to asthenospheric flow outwards to regions beneath the margins, as shown by tomographic studies (*Rickers et al.*, 2013; *Schoonman et al.*, 2017). The onset of this episode happened at a time of peak activity of the Iceland plume coincident with a reduction in the spreading rate in the NE Atlantic, linked to the dynamics of the Pacific plate (*Poore et al.*, 2009; *Iaffaldano and DeMets*, 2016). We note, however, that there was also renewed compressive stress from the Alps at this time as the continental crust of the Mont Blanc massif was emplaced (*Egli and Mancktelow*, 2013). That there must have been an element of compression in the final uplift is shown by the presence of the domes and intervening downward buckle of the LPS (Figure 12a,e).

9 Conclusions

Why are there mountains in Norway? This provocative and seemingly naïve question is still not fully answered by this study. However, as a first step towards solving the enigma, we have mapped the remnants of three peneplains that define the palaeic relief and estimated the ages of their formation.

We used an analogue approach based on digital elevation data, combining contour maps and profiles to produce our maps of the high plains of the palaeic relief of the Southern Scandes. Our analysis shows that the palaeic relief consists of three extensive surfaces of low relative relief separated by escarpments, typically 200–400 m high. We have established that the palaeic surfaces formed in post-Jurassic times, and that they cut across rocks of different lithology.

We have named the peneplains according to their elevation in the landscape: The Lower Palaeic Surface (LPS), the Middle Palaeic Surface (MPS) and Upper Palaeic Surface (UPS). These surfaces are found at altitudes of 1000–1400, 1300–1700 m and 1600–1900 m, respectively. The mapped extent of the LPS is around 90,000 km^2.

The erosion products of the formation of each surface formed fans or deltas in the sea areas around southern Norway. The palaeic surfaces were formed by the river erosion that transported sediment to the deltas. That they are flat and extensive shows that they are peneplains and that their base level must have been sea level. The LPS formed during the Miocene, the MPS during the Paleocene and the UPS during the Late Cretaceous after preceding episodes of subsidence and burial. Each surface was uplifted after its formation and each younger surface formed, again graded to sea level. The final uplift to their present-day elevations started prior to the glaciations in the early Pliocene. The late uplift caused rejuvenation of the relief, re-exposure of the Jurassic surface below the LPS and its partial destruction by incision of fluvial valleys. Most fluvial valleys were reshaped into glacial fjords and valleys during the Quaternary, but remnants of the fluvial erosion are preserved on the sides of the glacial valleys. The stepped peneplains were little eroded by ice and kept much of their pre-glacial appearance, and it seems likely that sedimentary covers protected the UPS and MPS after their formation.

Our study demonstrates that the Scandes, the Scandinavian EPCM, have not remained high since the Caledonian Orogeny, that they are not the result of footwall uplift during the formation of sedimentary basins to their west and that the palaeic relief is not the result of glacial erosion. We have shown that the high-level landscape is the result of repeated episodes of subsidence and uplift, burial and exhumation, driven, we have suggested, by sub-lithospheric forces and/or intra-plate stress. Such movements continued after the onset of nearby rifting and later sea-floor spreading when only subsidence is to be expected as a corollary of conventional plate tectonic theory. These observations need to be included in any quantitative model of the development of these and other mountains marginal to passive continental margins.

Acknowledgements

The Norwegian Petroleum Directorate supported this study. Dag Bering realized the importance of the study from day one. Comments and suggestions from the editor, an anonymous reviewer and reviewer Tony Doré improved the paper significantly.

Author contributions

JMB: Conceptualization (lead), data curation, formal analysis (equal), investigation (equal), methodology (lead), writing – review and editing (equal); **JAC:** Conceptualization (supporting), formal analysis (equal), investigation (equal), methodology (supporting), writing – original draft, writing – review and editing (equal); **PJ:** Conceptualization (supporting), funding acquisition, investigation (equal), project administration, writing – review and editing (equal).

Data availability

The Supplements related to this article can be accessed from the Mendeley Data repository (https://doi.org/10.17632/3dg4dk95z5.1) and contain topographical data, additional analysis and photographs:

S1: Contour map with interpretation of surfaces.

S2: N-S topographical profiles.

S3: E-W topographical profiles.

S4: Map of the surfaces for GoogleEarth.

S5: Conceptual sketches.

S6: Photographs of the surfaces, escarpments and 3-D display.

S7: Comparison of interpretations.

Competing interests

The authors declare no competing interests.

Peer review

This publication was peer-reviewed by Tony Doré and an anonymous reviewer. The full peer-review report can be found here: Review Report.

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