How old are the Norwegian mountains (Fig. 1)? Why is there a mountain range along the Atlantic margin of Scandinavia? It is surprisingly difficult to answer even the first of these questions, and we can address the second question only after the timing has been established.

Some 420 Ma, Laurentia, Baltica and Avalonia collided forming the Caledonian mountain chain that stretched from Scandinavia and East Greenland through Scotland and Ireland to eastern North America. Some geoscientists argue that the present-day mountains are just the remnants of these Caledonian mountains that have worn down slowly and gradually. The mountains eventually became lower and lower through those hundreds of millions of years, until the highest summit in Norway today reaches an elevation of ‘only’ 2.5 km. Those who favour this explanation base their hypothesis primarily on computer modelling that assumes continuous isostasy and a history of long-term erosion. They argue that the mountains (the top of the iceberg, so to speak) have been supported by a crustal root that has persisted since Caledonian times. This hypothesis has, however, been tested by seismic observations that have failed to find a root sufficient to support the present-day mountains (Fig. 2).

A second group—to which we belong—thinks that field observations show that there is good evidence from both Norway and Greenland that the Caledonian Mountains collapsed during the Devonian, shortly after their formation. Eclogite rocks, formed at depths...
of more than 50 km, were lifted close to the surface onto which Devonian sediments were being deposited.

In East Greenland, which made up a coherent landmass with Scandinavia during the formation of the Caledonian mountains, Permian marine sediments cover a peneplain eroded into the Caledonian rocks.

We know fairly well how collisional mountain ranges form, like the Alps, Himalayas and Andes. We do not, however, understand why there are mountains along many extensional (passive) continental margins. The present-day mountain chain along the western margin of Scandinavia (the Scandes) is one example and others are found in East and West Greenland, northeast Brazil, western India and southeast Australia. They occur in all climate zones, from the Arctic to the tropics. These mountain ranges have several features in common: the presence of elevated plateaux such as the high plain of Hardangervidda in Norway (see Figs 1 and 3), erosional truncation of the sedimentary strata along the oceanward side of the mountain ranges and a steeper slope on their oceanward side than towards the landward side. There is a debate raging about the age of these mountains.

Together with Paul Green and Johan Bonow (who are experts in thermochronology and geomorphology, respectively), we have published a paper in the Journal of the Geological Society, London, where we show evidence that the topography of the mountains in southernmost Norway is geologically young. We reached that conclusion by combining observations of landscape and geology with analysis of fission tracks in grains of the mineral apatite (see Box 1). Here we outline our key arguments.

Southern Norway was buried below thick covers of rock 23 Ma

Our study area covers a region south of Bergen and west of Oslo that makes up the southern half of an elongated, dome-shaped mountainous massif (Fig. 1). An extensive plain about 1200 m above sea level (masl), known as Hardangervidda, occupies the central part of this massif (Fig. 3(a)). The bedrock slopes downwards from Hardangervidda towards the coast in the west, south and southeast.

Analysis of our apatite fission-track analysis data (AFTA data; see Box 1) shows that this part of Norway was deeply buried below a cover of rocks in early Miocene times (23 Ma). At this time, a phase of uplift started to affect Scandinavia, north and east of the Kattegat, that lifted the geological strata above sea level and thereby exposed them to erosion that removed many hundreds of metres of this cover. Because temperature increases steadily with depth below the surface, removal of rock by erosion leads to cooling of the underlying rock layers, and this can be detected by AFTA.

AFTA data from 27 rock samples from southernmost Norway combined with results from offshore boreholes and from samples from southern Sweden show that the present-day surface began to cool due to erosion between 23 and 21 Ma (in the early Miocene; Fig. 4).
Big river systems, originating in Norway and Sweden, began to deposit sediments in Denmark at the same time, showing that the uplifting area was being eroded. The AFTA data thus tell us when the surface of Earth was uplifted and started to cool because of erosion. The analysis also gives us the temperature of a rock sample when the cooling began. We know that the temperature in the Earth’s interior increases with depth, by some 15–30°C/km depending on the rock properties, so we are able to estimate the thickness of the cover rocks that were once present.

We analysed rock samples from the coast and from the interior. The results show that samples from today’s coast were at about 60°C when cooling began 23 Ma, whereas the results from the interior indicate that rocks on the surface of Hardangervidda at an elevation of 1200 m were somewhat colder. In both cases, the palaeotemperatures can be explained by burial below a cover of insulating rocks.

We also used the variation in determined palaeotemperatures across southern Norway to estimate the thickness of the rocks that have been removed since 23 Ma (Fig. 5(a)). We find that about 1500 m of sediments covered the coastal areas around Stavanger and Bergen (where Jurassic sediments are preserved in a fracture zone), while about 750 m of Caledonian metamorphics and younger strata covered the rocks that today are exposed on Hardangervidda.

In other words: The high plain of Hardangervidda did not exist 23 Ma (in the early Miocene).
Hardangervidda: a plain graded to base level by Miocene rivers

Hardangervidda is a relatively flat plateau at an elevation of about 1200 masl (Figs 1 and 3). However, at the beginning of the Miocene, a thick cover laid on top of the rocks that today are exposed on Hardangervidda. This cover was removed by river erosion, which began to cut into the landscape as a consequence of the early Miocene uplift. The erosion continued for millions of years until Hardangervidda had been graded to the well-defined plain, which is seen today.

At the time when Hardangervidda had been eroded to a plain, it must have been close to either a regional resistant level or the adjacent ocean. Since there is no resistant level in Norwegian geology, this implies that the plain must have been close to sea level by the time of its final formation (Fig. 5(b)) and must have been raised to its present elevation of 1200 m afterwards (Fig. 5(c)). This conclusion also implies that today’s inclined slopes between Hardangervidda and the coast were buried below sediments and that the plain at the level of Hardangervidda must have cut across those sediments too.

Today, deep valleys and fjords cut into the edge of Hardangervidda (Fig. 6). The deeper parts of these valleys are clearly formed by glacial erosion, but remains of V-shaped river valleys are still present high on the valley sides. The preservation of these valley shoulders provides evidence that the initial incision of the uplifting plains was by rivers, in which the resulting fluvial valleys were then over-deepened by glaciers and that the glacial erosion of the plateaus was insignificant.

In other words: Hardangervidda started to form during the Miocene as part of a vast plain. The plain extended across the basement rocks of Hardangervidda and also across the pile of sediments that then covered the present mountain slopes. The plain was uplifted to its present altitude during the Pliocene and Pleistocene, but the part of the plain that extended across the sediments has been eroded away.

Hilly basement relief: remnants of a landscape from the time of dinosaurs

Our AFTA data also show that an earlier phase of uplift and erosion affected Scandinavia in the Middle Jurassic, 175 Ma, which resulted in the formation of an extensive erosion surface across basement rocks (Fig. 7). That episode has left a lasting impact on the landscape.

Scandinavia’s climate at that time was sub-tropical, warm and humid. Water from the warm rain seeped into fractures in the basement and transformed the feldspars in granitic rocks into clays, particularly kaolin, resulting in the formation of a so-called saprolite (a
Our AFTA results show that these rocks were buried below a thick cover prior to the onset of early Miocene uplift (Fig. 5(a)). We therefore infer that Late Jurassic and younger sediments covered the bedrock along the coast between Stavanger and Bergen 23 Ma. This cover protected the fracture valleys and hilly relief until they were re-exhumed after later episodes of uplift.

In other words: The basement rocks were exposed and weathered in Jurassic times and subsequently buried below a protective cover of sediments. Today, we see the remnants of this weathered landscape as hilly relief and fracture valleys at elevations up to 1000 masl.

The mountains of southernmost Norway: uplifted Miocene plains above re-exposed Jurassic landscapes

Hardangervidda was formed by river erosion to a plain near sea level during the Miocene. Today it lies 1200 masl (Fig. 5c). We infer that Late Jurassic and younger sediments covered the bedrock along the coast between Stavanger and Bergen 23 Ma. This cover protected the fracture valleys and hilly relief until they were re-exhumed after later episodes of uplift.

In other words: The basement rocks were exposed and weathered in Jurassic times and subsequently buried below a protective cover of sediments. Today, we see the remnants of this weathered landscape as hilly relief and fracture valleys at elevations up to 1000 masl.
quent Ice Age amplified the effect of the initial uplift by removing a huge load of rocks from the land areas and isostatic compensation for the loss of this load caused further uplift.

The late uplift phase in the Pliocene raised the sediment-covered slopes below Hardangervidda to well above sea level, so that rivers could erode their cover and wash it into the sea, leaving the hard bedrock of Hardangervidda as a remnant of the plain that once extended across all of southern Norway. The hilly relief formed by weathering in the Middle Jurassic was exhumed to the surface. Deep valleys and fjords have cut into the uplifted landscape, but there are sufficient remnants of the Mesozoic terrain to map its presence over wide areas.

In other words: A long history involving phases of erosion, burial and uplift explains the contrasts between the plains of Hardangervidda, the hilly relief on the slopes of the rock massif and the deep valleys, which cut the massif.

New dimensions to old conclusions

The notion that the Norwegian mountains are relatively young is not new. The Norwegian geologist Hans Reusch argued for this hypothesis in 1901. He highlighted the contrast between the elevated plains and the deep valleys. He referred to the plains as the palaeic (old) surface because he considered that rivers and—later on—glaciers must have incised into an older landscape defined by the elevated plains. Reusch therefore concluded that the plains had been lifted to their present elevation in more recent geological time.

We have added several new dimensions to the old story: Multiple episodes of uplift and subsidence have shaped the landscape since the collapse of the Caledonian mountains. Uplift, erosion and weathering in Middle Jurassic times were followed by subsidence and burial. Finally, two phases of uplift and erosion affected the region in the early Miocene and early Pliocene. Hardangervidda was formed as part of an extensive plain near sea level by uplift and erosion starting in the Miocene. The plain was afterwards raised to its present elevation, but the only parts of the plain that remain today are where it cut across hard rocks forming the present-day mountain plateau. The sloping bedrock surface between Hardangervidda and the coast, which was buried below a thick sedimentary cover until this late stage, was re-exposed and the hilly relief, the result of weathering processes almost 200 Ma, was revealed.

Are the Scandes remnants of a 400-Myr-old mountain chain or did they reach their present elevation only after uplifts during the last 20 Myr? We have presented observations and arguments in favour of...
the transient nature of these mountains, and in other publications we have reached the same conclusion for other elevated passive continental margins. What processes could have caused a history of uplift and subsidence? Upwelling in the mantle? Compression that folded the crust as a whole caused by far-field forces and/or maybe pressure-driven flow in the asthenosphere? The challenge ahead of us is to identify the processes that led to the uplift and subsidence of the Scandes and of the mountains along many other so-called passive continental margins around Earth.

Suggestions for further reading

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