

# Possible Mesozoic Mantle Plume Activity beneath the Continental Margin of Norway

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Based on recent geological and geophysical information from the Norwegian/Greenland Sea and North Sea areas, and on earlier geomorphological information interpreted in terms of regional drainage pattern evolution, it is concluded that the More-Jotunheimen and Norrbotten-Troms uplands may be erosional remnants of two large, pre-Tertiary, mantle plume-generated domal uplifts. These were centred on the adjacent parts of the present continental shelf and slope, where linear gravity highs and elongate sedimentary troughs may represent mantle plume-generated mafic intrusions and rifts. The mantle plume activity probably occurred in Mesozoic time, possibly in the Jurassic, long before the onset of Early Tertiary ocean-floor spreading in the Norwegian/Greenland Sea area. The inferred rifts and intrusions appear to form a northern extension of pre-splitting tectonic activity along the present North American and north-west European Atlantic margins.

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## Introduction

Dome-shaped crustal uplifts, with ensuing rifting, volcanism and formation of tectonic triple junctions, are currently regarded as surface manifestations of mantle plume activity beneath the lithosphere (Morgan 1971; Wilson 1972, 1973; Burke & Whiteman 1973). In a typical evolutionary sequence mantle plume-generated uplifts develop through rifting, with the formation of three crestral rifts meeting at triple junctions designated 'rrr' ('rift-rift-rift') junctions, into spreading 'RRR' junctions (Burke & Whiteman 1973). Continental triple junctions are considered to have developed into diverging, accreting lithospheric plate margins causing continental break-up and ocean-floor spreading (Burke & Dewey 1973). An example is the Afar RRR junction in Ethiopia, with active spreading on the Red Sea and Gulf of Aden arms and incipient spreading on the Ethiopian Rift arm (Burke & Whiteman 1973). These rifts form the diverging, accreting margins of the Arabian, Nubian and Somalian lithospheric plates (Darracott et al. 1973).

In other examples only two arms of a triple junction reach the spreading stage, while the third rift forms the 'failed' arm of a 'RRr' triple junction (Burke & Whiteman 1973). The occurrence of triple junctions with two or even three 'failed' arms has also been suggested (Burke & Whiteman 1973; Burke & Dewey 1973; Naylor et al. 1974; Whiteman et al. 1975). Examples of mantle plume-generated uplifts without associated rifting are the Rhodesia and Vaal swells in southern Africa (Burke & Wilson 1972), the Adamawa

uplift in equatorial Africa (Burke & Whiteman 1973) and the Colorado Plateau in North America (Wilson 1973).

Morgan (1971) considered mantle plume activity to be the driving force of lithospheric plate motion. Wilson (1972) and Burke & Dewey (1973) have suggested that divergent plate motion is initiated following the emplacement of axial dykes in crestral rifts on swells above mantle plumes, and that accreting plate margins develop from rifts in the lithosphere linking neighbouring plume tops in the asthenosphere. Burke & Wilson (1972), in proposing the average lifetime of individual mantle plumes to be of the order of 100 m.y., ascribed the changing patterns and rates of plate motion to the influence of changing competition among shifting arrays of plumes of different ages and of variable intensities of activity.

The present paper presents evidence suggesting that, in mainland and off-shore Norway, two instances of mantle plume-generated doming and rifting preceded the Early Tertiary initiation of active ocean-floor spreading in the Norwegian/Greenland Sea. It is concluded that the present uplands in the Møre-Jotunheimen and Troms-Norrbotten areas may be remnants of the suggested domal uplifts, and that the Mesozoic sedimentary troughs on the Norwegian continental shelf and slope were formed as a result of rifting associated with them. These events may be integrated into the post-Palaeozoic geotectonic history of the North European-North American region.

### Ocean-floor spreading in the North Atlantic-Arctic region

The final closing of the Palaeozoic proto-Atlantic ocean in Late Palaeozoic time by continental collisions of Africa, North America and South America (Coney 1973) completed, together with the collision between the European/Russian and Siberian platforms (Hamilton 1970; Ostenso 1973), the assemblage of the universal Pangaeans continent (Dietz & Holden 1970); Europe and North America had already collided at an earlier stage (Coney 1973). The Mesozoic re-organization and the subsequent renewal of lithosphere plate motion, causing the break-up of Pangaea (Dietz & Holden 1970), constitute the geotectonic point of departure for the currently continuing ocean-floor spreading and continental drift in the North Atlantic-Arctic region.

Active ocean-floor spreading in the North Atlantic commenced about 180 m.y. ago when Africa separated from North America (Le Pichon 1968; Dietz & Holden 1970; Vogt et al. 1970; Pitman & Talwani 1972; Bott 1973a; Burke & Dewey 1973; Laughton 1975).

In the Early Cretaceous (120 m.y. ago), ocean-floor spreading produced a widening split between the Grand Banks of Newfoundland and the Iberian Peninsula, and at the same time opened up the Bay of Biscay by a counter-clockwise rotation of Iberia with respect to Europe (Laughton 1975). This rotation stopped in the Late Cretaceous (80 m.y. ago), and active spreading is then thought to have started along an axis running north-westwards from the Bay of Biscay into the Labrador Sea (Laughton 1975). As the Labrador Sea

started to develop, Greenland, Europe and Iberia formed parts of a single plate separating from North America (Laughton 1971, 1975).

In the Arctic Ocean area, complex lithospheric plate motion involving divergent, convergent and transform plate interactions appears to have started in the early Mesozoic (Ostenso 1973, 1974), although the Beaufort Sea area of the Canadian Basin possibly had been in existence as an ocean basin (the Hyperborean Sea) since the Early Palaeozoic (Churkin 1969, cited in Ostenso 1973). Spreading in the Arctic Ocean was originally proceeding from the Alpha Ridge but switched to the Nansen Ridge about 47 m.y. ago, thereby splitting off the Lomonosov Ridge from Eurasia as a strip of continental crust, which now separates the Canadian Basin from the Siberian Basin (Ostenso 1973, 1974). In Mesozoic time the spreading axis in the Arctic Ocean may have been coupled to the Labrador Sea spreading axis by a major fracture zone, the Wegener fault (Wilson 1963, Burke & Dewey 1973).

South of Greenland the Cape Farewell triple junction (Pitman & Talwani 1972; Burke & Dewey 1973), possibly initiated in the Jurassic, became a RRR junction with active spreading on all three arms in the Late Palaeocene. This caused Greenland to become a separate plate by being split off from Europe along a spreading axis which opened up the Norwegian/Greenland Sea (Avery et al. 1968; Vogt et al. 1971; Johnson et al. 1972; Pitman & Talwani 1972; Bott 1973a; Ostenso 1973; Laughton 1975).

Greenland rejoined the American plate when a change in spreading pattern in the Middle Eocene (42/47 m.y. ago) stopped further opening of the Labrador Sea. Simultaneously, relatively minor changes affected the local North Atlantic, Norwegian/Greenland Sea and Arctic Ocean spreading centres.

Since the Middle Oligocene no major changes in spreading pattern are known to have occurred in the North Atlantic-Arctic region (Phillips & Luyendyk 1970; Vogt et al. 1971; Johnson et al. 1972; Bott 1973a; Ostenso 1973, 1974; Laughton 1975).

### The Norwegian/Greenland Sea area and its spreading history

Within this oceanic province, the Mid-oceanic Ridge is segmented into the Kolbeinsey Ridge between Iceland and the transverse Jan Mayen Fracture Zone (Fig. 1), Mohn's Ridge between the Jan Mayen and Greenland Fracture zones and the Atka (or Knipovich) Ridge between the Greenland and the Spitsbergen Fracture zones (cf. Talwani & Eldholm 1974). This stretch of the Mid-oceanic Ridge separates the Norwegian Basin, to the south-east, from the Greenland Basin, to the north-west. Both these basins are bordered on their landward sides by a continental slope and shelf.

Structurally important physiographic elements within the Norwegian Basin are (Fig. 1): the Vøring Plateau, a relatively deep oceanward protrusion from the Norwegian continental slope; the Jan Mayen Ridge, a narrow micro-continental strip extending southwards from the volcanic Jan Mayen Island towards the Iceland-Faeroe Plateau (Johnson et al. 1972); and the Aegir

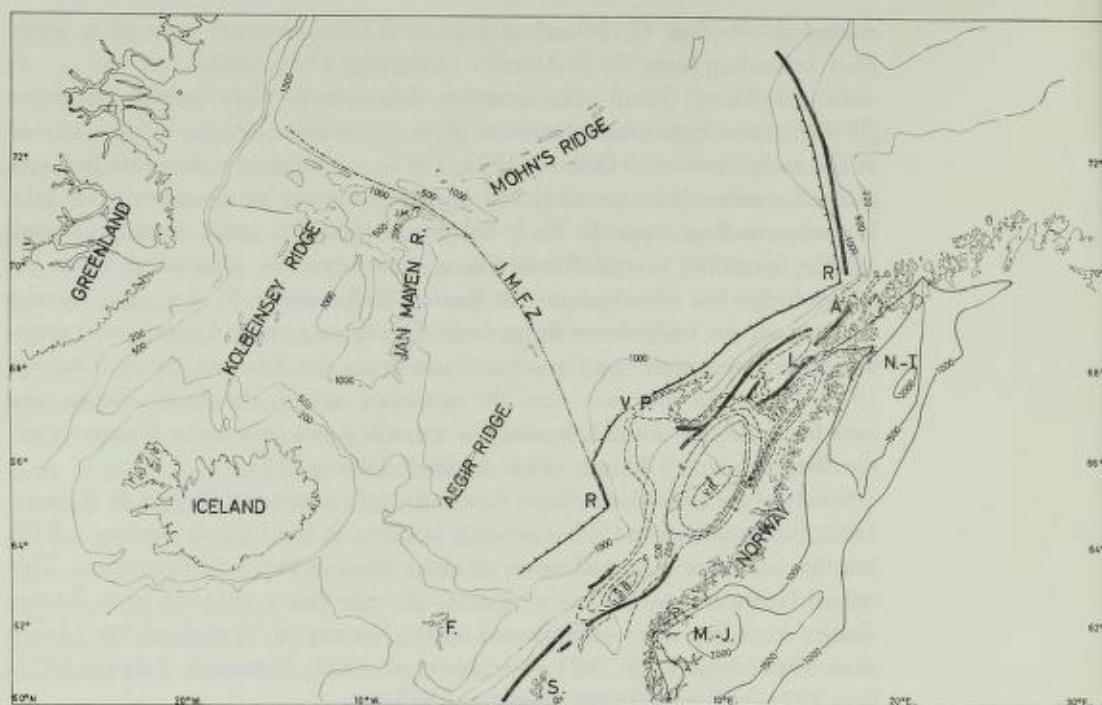


Fig. 1. Map of the Norwegian/Greenland Sea area (Redrawn after Talwani & Eldholm 1972 and Talwani & Grønlie, in press; Mercator projection).

A — Andoya; F — the Faeroes; J.M. — Jan Mayen island; J.M.F.Z. — Jan Mayen Fracture Zone (dash-dot line); L — Lofoten; M.-J. — Møre-Jotunheimen upland area; N.-T. — Norrbotten-Troms upland area; R — continental margin re-entrants; S — Shetland; S.B. — Stadt Basin; V.B. — Vøring Basin; Vf.B. — Vestfjord Basin; V.P. — Vøring Plateau. Thin, continuous lines: 200-, 500- and 1000-fathom isobaths.

Dashed, numbered lines on Norwegian continental margin are approximate isopach contours of pre-Tertiary sediments with thickness in km (adapted from Talwani & Eldholm 1972, Figs. 13 and 15). Thick, ticked line: ?oceanic crust/continental crust boundary along the Norwegian continental margin. Short, thick lines: linear gravity highs on Norwegian and Barents shelf edges and slopes. Numbered contours on mainland Scandinavia: 'enveloping surface' (modified after Gjessing 1967; heights in metres a.s.l.).

Ridge, a NNE-SSW trending chain of abyssal seamounts in the southern half of the Norwegian Basin (Hinz & Moe 1971) representing an extinct, buried ocean ridge/rift valley structure (Eldholm & Windisch 1974).

Active ocean-floor spreading in the Norwegian/Greenland Sea area started about 60 m.y. ago, according to interpretations of magnetic anomalies in terms of the geomagnetic time scale of Heirtzler et al. (1968); anomaly no. 24 (c. 60 m.y. old) is the oldest magnetic anomaly identified in segments of oceanic crust immediately adjacent to continental crust in this area (Avery et al 1968; Talwani & Eldholm 1972, 1974).

North of the Jan Mayen Fracture Zone, spreading has apparently always proceeded from Mohn's Ridge. In the area between the Iceland-Faeroe Plateau and the Jan Mayen Fracture Zone, ocean-floor spreading has been more complex: in the first period of active spreading, from c. 60 to c. 42 m.y. ago,

the Aegir Ridge was the spreading axis (Vogt et al. 1970). Later (cf., Laughton 1975, p. 187), the spreading centre migrated westwards, eventually initiating spreading beneath the Greenland continental margin and thereby splitting off a chip of continental crust, overlain by a thick sedimentary pile, which now forms the Jan Mayen Ridge (Fig. 1; Johnson & Heezen 1967). A further, but so far unconfirmed, westward migration of the spreading centre has been inferred to explain the asymmetrical position of the presently active Kolbeinsey Ridge between the continental Jan Mayen Ridge and the Greenland continental margin (Talwani & Eldholm 1972, Bott 1973a).

The Jan Mayen Fracture Zone (Fig. 1) forms a belt, up to 75–100 km broad (Avery et al. 1968, Johnson 1968), transecting the oceanic crust between Norway and Greenland and consisting of en échelon fault scarps and ridges with small intervening deep basins containing up to more than 2 km of sediments (Johnson & Heezen 1967; Eldholm & Windisch 1974). The island of Jan Mayen, with the active volcano Mt. Beerenberg (Gjelsvik 1970; Siggerud 1972) occurs within the zone. The Jan Mayen Fracture Zone can be inferred to represent the fossil trace of transform faults between the offset spreading axes abutting against it (Fox et al. 1969); the Aegir and Mohn's ridges during the period from about 60 to about 42 m.y. ago (or later; cf. Laughton 1975), and the Mohn's and Kolbeinsey ridges from about 10 m.y. ago (Hinz 1975).

The Vøring Plateau, between about 66° and 68.5°N, forms a large oceanward protrusion (surface area > 21,000 km<sup>2</sup>; Johnson et al. 1968) from the continental slope off Norway at roughly the 1,000 fathom depth level. Its structure and origin have been variously interpreted. The Plateau is dissected by a NE–SW trending buried escarpment (Talwani & Eldholm 1972, 1974). The inner, south-eastern portion of the Plateau consists of up to 9 km of Mesozoic and Cenozoic, and possibly also late Palaeozoic, sediments deposited on a basement inferred to be of continental type (Talwani & Eldholm 1972; Sellevoll 1973, 1975). The outer, north-western portion of the Vøring Plateau has up to c. 1 km of Cenozoic sediments overlying a basement interpreted as either oceanic (Talwani & Eldholm 1972, 1974) or continental (Hinz 1972). Talwani & Eldholm (1972, 1974) considered that the Vøring Plateau escarpment marks the boundary between landward continental crust and oceanward oceanic crust, created by Early Tertiary ocean-floor spreading.

### The Norwegian continental margin

Talwani & Eldholm (1972) divided the continental margin of Norway into three sedimentary provinces (Fig. 1): A) a southern province, south of c. 67°N, including the Stadt and Vøring sedimentary basins with thick accumulations of mainly pre-Tertiary sediments, overlain by thinner Tertiary and Quaternary deposits and wedging out near the coastline; B) the Lofoten–Vesterålen province to the north, characterized by generally having a relatively thin cover of sediments (1 to 2 km thick) but with much thicker (> 4 km)

deposits in a deep sedimentary trough in Vestfjorden (Nysæther et al. 1969); and C) a northern sedimentary province, north of Andøya, with sediment distribution and structures similar to those in the southern province. Just to the north of Andøya a downfaulted trough contains up to 4.8 km of sediments (Sundvor 1971).

Narrow, linear, gravity highs occur along the shelf edge (Fig. 1; Talwani & Eldholm 1972, 1974; Talwani & Grønlie, in press). From the available geophysical evidence, Talwani & Eldholm (1972, 1974) concluded that these anomalies occur in continental crust-type basement and that in places they form structural ridges protruding into the overlying sedimentary rocks. They interpreted the gravity highs as representing dense, metamorphic Precambrian rocks, similar to those underlying the Lofoten area, and suggested that such rocks may form a more or less continuous, long and narrow belt running along the shelf edge from Lofoten all the way to the Lewisian region of NW Scotland where a linear gravity high has, in a general way, been similarly interpreted (Watts 1971). The coinciding of the shelf edge with linear gravity highs was explained by Talwani & Eldholm (1972, 1974) by the tentative assumption that the suggested belt of high-density Precambrian rocks had pre-determined the location of the shelf edge by acting as a landward hinge for the subsidence of the newly formed continental margin after the Early Tertiary opening of the Norwegian Sea.

In the present paper the linear gravity highs along the Norwegian shelf edge are tentatively interpreted as being caused by mafic dykes, genetically related to ?Mesozoic mantle plume activity. In this interpretation the coincidence of the gravity highs with the shelf edge is considered to be a consequence of the Early Tertiary continental splitting in this region having partly followed older zones of weakness in the lithosphere, i.e., parallel to rifts and dyke intrusions associated with older, 'abortive', mantle plume activity.

The linear gravity high along the base of the continental slope off the Barents shelf (Fig. 1; Talwani & Eldholm 1972, 1974; Eldholm & Windisch 1974; Talwani & Grønlie, in press) was tentatively interpreted (Talwani & Eldholm 1972, 1974; Eldholm & Windisch 1974) as representing a deeply buried fracture zone, called the Senja Fracture Zone, produced by shearing during the initial, Early Tertiary opening of the Norwegian/Greenland Sea. An alternative interpretation, tentatively suggested here, is that this linear gravity high, like the ones along the continental margin off Norway, may represent mafic material intruded into the continental crust in connection with (?) Mesozoic mantle plume activity. Later, continental splitting may have occurred along this zone of dilation to produce a fracture zone along a sheared continental margin, bordering the Barents shelf.

## Tectonic events in the North Atlantic–Arctic region prior to active ocean-floor spreading in the Norwegian–Greenland Sea

Along and near many of the continental margins created by the onset of ocean-floor spreading in the North Atlantic–Arctic Region, continental break-up was heralded by early tectonic events involving rifting and basin sedimentation with or without igneous activity. Such events, a synopsis of which is presented below, appear to have preceded the opening of the ocean basins by up to several tens of millions of years.

Hallam (1971) presented evidence showing that the southern North Atlantic experienced a period of rifting some 50 m.y. before the actual continental separation in that area. Such pre-opening tectonism produced Triassic (c. 230–220 m.y. ago) rifts with thick sedimentary piles and basic dyke intrusions along the Atlantic continental border of North America from Alabama to Labrador (King 1959; Coney 1973; Vogt 1973).

Rifting, and perhaps minor spreading (van der Linden 1975), took place in the Labrador Sea in the Jurassic, during the initial development of what was later to become the Cape Farewell Triple Junction (Pitman & Talwani 1972).

The basement of the Rockall Trough (Bott & Watts 1971), south-east of the continental Rockall Plateau (Scrutton 1972), can be interpreted as oceanic crust or as thinned and subsided continental crust underlying a thick pile of sediments, assumed to have been deposited in an early Red Sea-type trough formed contemporaneously with the initial split further south, along the eastern shelf of North America.

Along the continental shelf and margin north of Scotland, sedimentation during the Mesozoic was probably largely controlled by contemporaneous faulting along older 'Caledonian' NNE directions (Bott & Watts 1971). The Faeroe–Shetland Trough was in existence before the onset of Tertiary ocean-floor spreading (Bott 1975), and probably formed by rifting simultaneously with the Rockall Trough on oceanic or thinned continental crust in the Early Mesozoic. It has been inferred to be bordered by continental crust both to the north-west and the south-east (Bott 1973a, 1975), but it has also been considered that the basement to the north-west of the flanking Faeroe–Shetland escarpment may be oceanic (Talwani & Eldholm 1972, 1974).

Fault activity during the Mesozoic, mostly pre-Mid Jurassic in age, formed a complex, NE–SW trending sedimentary trough in the Moray Firth, Scotland (Bacon & Chesher 1975). Faulted Mesozoic basins also occur on the Shetland–Orkney shelf and in the Minch (Bott 1975), and active graben downfaulting in the North Sea during this period (Whiteman et al. 1975; Ziegler 1975) produced the complex North Sea System of interlinked troughs (Naylor et al. 1974; Whiteman et al. 1975).

Bott (1975) suggested that the Stadt and Vøring basins, on the Norwegian continental margin, are NE-ward extensions of the Faeroe–Shetland Trough; and Whiteman et al. (1975) have suggested that the Stadt and Vøring basins, the Faeroe–Shetland Trough and the Northern North Sea Trough form the

three 'failed' arms of a Late Palaeozoic–Early Mesozoic rrr triple junction. The Middle/Upper Jurassic to Lower Cretaceous sedimentary rocks on Andøya in Vesterålen were deposited during periods of downfaulting in Middle Jurassic and Early Cretaceous times, and were subject to further faulting in the Early Tertiary (Dalland 1975). The Andøya sediments form a small, landward extension of the much larger and thicker, NW–SE trending sedimentary basin to the east and north of the island (Sundvor 1971; Talwani & Eldholm 1972; Dalland 1975). In Trøndelag, central Norway, the occurrence of several hundred boulders of Middle Jurassic sedimentary rocks in Beitstadfjorden, a tributary to the inner Trondheimsfjord, has suggested the presence of a small, downfaulted, Mesozoic sedimentary basin in this area (Ofstedahl 1972).

Thick Mesozoic and (?) Late Palaeozoic sedimentary deposits in downfaulted troughs, parallel to the later-established continental margin, thus appear to occur more or less continuously along the Atlantic coast of North America and its pre-drift continuation along the continental margin of north-western Europe. These sedimentary troughs include the Rockall, Minch and Faeroe–Shetland (West Shetland Basin of Naylor et al. 1974 and Whiteman et al. 1975) troughs on the British continental margin, and the Stadt, Vøring, Vestfjord and Andøy sedimentary basins on the Norwegian continental margin. In a pre-drift reconstruction of the Greenland/Norwegian Sea area, the continental Jan Mayen Ridge with its thick sedimentary pile, split off from the Greenland shelf by sea floor spreading from the Kolbeinsey Ridge (or its immediate, unidentified precursor), would fit into the re-entrant in the continental margin south-east of the inner part of the Vøring Plateau (Fig. 1); here it would appear to fill in the gap between the Mesozoic trough deposits of the Faeroe–Shetland Trough and the Vøring Basin (cf. Talwani & Eldholm 1974, Fig. 2).

Successive events of rifting and downfaulting in the Central Graben of the North Sea in Middle Jurassic to Lower Cretaceous times were accompanied by marginal uplifts with ensuing sub-aerial erosion (Ziegler 1975), and large uplifts in the northern parts of the North Sea during the Middle Jurassic are evidenced by the development of major regressive sedimentary facies sequences (Sellwood & Hallam 1974; Ziegler 1975). Regional uplift in the North Sea area is also evidenced by a major, complex unconformity beneath Cretaceous sediments; in the northern North Sea this unconformity constitutes a major trap for oil (Howitt 1974). The concurrence of regional uplifts and Mesozoic rifting in the North Sea area seems, therefore, to be well established.

## Mantle plume activity beneath the Norwegian continental margin

### REGIONAL TECTONICS AND GEOMORPHOLOGICAL SETTING

Burke & Dewey (1973) have suggested that four, pre-Tertiary, mantle plume-generated triple junctions occur along the Rockall and Faeroe–Shetland troughs, and Naylor et al. (1974) and Whiteman et al. (1975) recorded three in the central and southern parts of the North Sea. Further north, structural features



on the Norwegian continental shelf together with physiographic and geomorphological features of the Norwegian mainland appear to give evidence of early (?Jurassic) mantle plume activity in two additional areas: the Møre-Jotunheimen and adjoining offshore areas in West Norway, and the Troms-Lofoten-Norrbotten area of North Norway and adjoining parts of Sweden. In both areas the inferred mantle plume activity was arrested at an early stage, before the formation of fully developed triple junctions.

The Tertiary oblique uplift of the Scandinavian landmass (Strøm 1948; Holtedahl 1953; Rudberg 1954) has been considered in general terms as a side effect of the opening-up of the Norwegian Sea by ocean-floor spreading about 60 m.y. ago (Ofstedahl 1972; Talwani & Eldholm 1972; Torske 1972; Nilsen 1973). Later marginal subsidence resulted in a large flexural downwarp, with ensuing Tertiary sedimentation on the submerged continental margin with its Mesozoic sedimentary troughs (Holtedahl & Sellevoll 1971; Talwani & Eldholm 1972; Sellevoll 1975).

The physiographical 'enveloping surface' of Norway (Gjessing 1967) shows two elongate highs, one in the Møre-Jotunheimen area and another in the Lofoten-Ofoten-Troms area and adjoining parts of Norrbotten in Sweden. Both highs are in close proximity to areas exposing the deepest crustal sections within the Scandinavian Caledonides and both are situated on the landward side of sharp re-entrants in the continental margin (Fig. 1; Rudberg 1954). Continental margin configurations such as these are often associated with mantle plume-generated triple junctions (cf. Burke & Dewey 1973; Burke & Whiteman 1973).

The Tertiary oblique uplift of the Scandinavian landmass has been regarded as the first major rejuvenating event to occur after a protracted period of denudation (Strøm 1948; Holtedahl 1953, 1960; Rudberg 1954; Gjessing 1967). The character of the landscape which was rejuvenated by the Tertiary oblique uplift has been much debated; a review of the differing opinions and the evidence presented to support them is outside the scope of the present paper, except where they may be directly applied in the present context. Opinions have differed on whether the physiography immediately before the uplift was dominated by a peneplain, by a rolling landscape of old age or whether several peneplains and other erosion surfaces, deriving from older, sequential cycles of erosion were being downgraded simultaneously. Another matter of debate and differing opinions has been the amount and geomorphological significance of subsequent glacial erosion during the Pleistocene ice ages. Reviews have been given by Holtedahl (1953, 1960), Rudberg (1954) and Gjessing (1967).

#### DEVELOPMENT OF DRAINAGE PATTERNS

Evidence has been presented to show that prior to the Tertiary uplift the main drainage divide in central Scandinavia was further east than at present (Ångeby 1947, 1955), and that the Tertiary uplift displaced the divide westwards, towards the Norwegian coast, from where the renewed erosion displaced it eastwards again.

Holtedahl (1953) pointed out the similar directions of the drainage pattern in central Sweden and that of a number of transverse, glacially eroded troughs along the inner part of the continental shelf in mid-Norway. He speculated that these features could constitute parts of old drainage systems whose missing, intervening portions in mainland Norway had been destroyed by later erosion. Such drainage systems could have been old, pre-Tertiary river valley systems draining the central parts of Scandinavia towards the west-northwest, across the partially or completely downwasted Caledonian mountain chain and into the epicontinental sea between Greenland and Norway. The common orientation of central Swedish rivers and Norwegian, transverse, glacially eroded troughs indicate the possibility that the pre-Tertiary land surface sloped, probably gently, towards the WNW in this region.

A general and regional drainage direction towards the WNW in central Scandinavia would be consistent with the widespread occurrence of retroverse rivers in central Sweden (Hjulström 1936; Rudberg 1954). It is also consistent with the inferred existence of an epicontinental sea in the northern extension of the North Sea depositional basin during Late Palaeozoic and Early Mesozoic times (Talwani & Eldholm 1972; Dunn 1975), since the Baltic Sea area appears to have been subject to continuous subaerial erosion from Late Devonian time to the Late Tertiary formation of the Baltic Sea by epeirogenic subsidence (Martinsson 1960). The present area of the Baltic Sea was drained by major rivers flowing southwards east of Gotland towards the Danzig depression. These relations suggest that, during these periods, the Baltic Shield was a largely positive feature, lacking the present Baltic Sea depression. By implication, the drainage divide may then be inferred to have been displaced eastwards from the orographic axis of the Caledonian mountain chain as denudation of this Early Palaeozoic feature progressed. The question of the pre-Tertiary position of the main drainage divide is closely related to the question of the time of the final downwasting of the orographic Caledonides.

The Tertiary uplift tilted the land-surface towards the ESE, and later Tertiary downwarp along the newly formed continental margin may have resulted in a welt-shaped upland along mid-Norway which was rapidly affected by erosion, guided by bedrock structures to form a subsequent drainage pattern. This would have disrupted the former continuity between the eastern and western parts of the old, WNW-directed drainage pattern. Such a sequence of events on land in mid-Norway may be reflected in the offshore sedimentary sequence by the occurrence of WNW-wards prograded, coalesced deltas well up in the Tertiary sequence between c.  $63\frac{1}{2}^{\circ}\text{N}$  and  $65^{\circ}\text{N}$  off the Trøndelag coast (Sellevoll 1975), since a regressive, prograding sequence would be expected to follow an earlier, non-deltaic, transgressive sequence during the waning stages of coastal downwarping in an area with a continuing high rate of sediment influx (Curry 1969). According to the present model the deltaic deposits should consist, to a large extent, of material eroded from the welt-shaped upland during the initial, Tertiary development of the subsequent drainage pattern in this area.

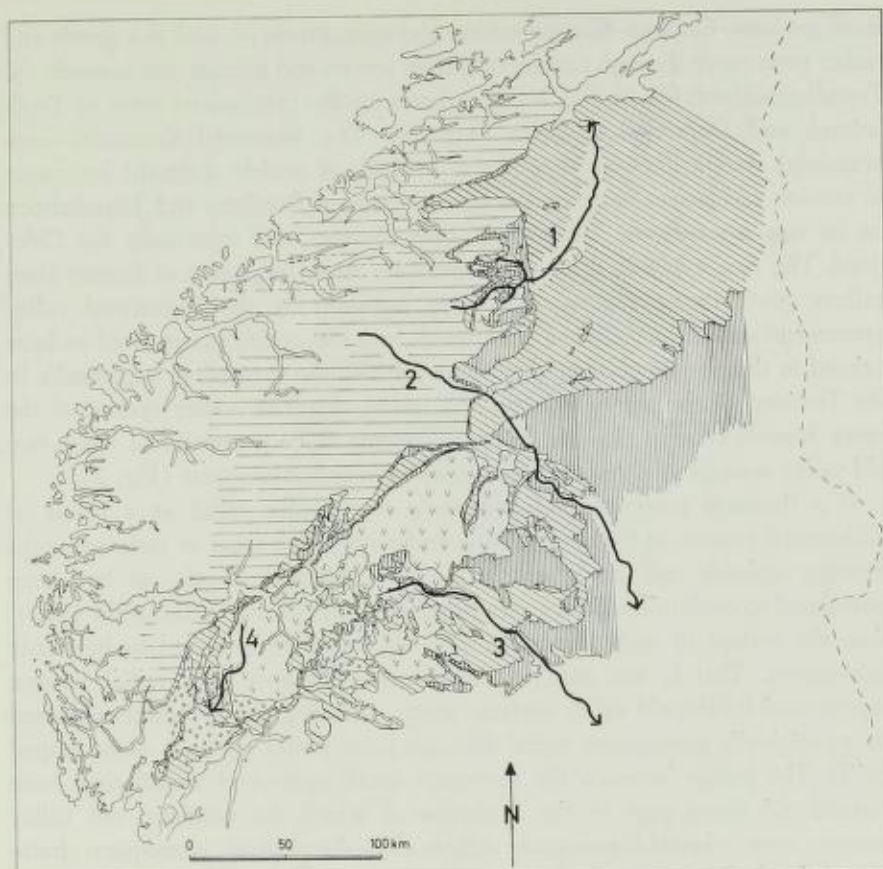


Fig. 2. Sketch map of west-central South Norway showing bedrock geology (simplified after Holtedahl & Dons 1960) and old drainage systems (1-4): 1) Sunndal-Drivdal-Gauldal system (Barrett 1900); 2) Vermedal-Raumadal-Gudbrandsdal system (Ahlmann 1919); 3) Lærdal-Valdres system (Ahlmann 1919); 4) Stalheimsdal-Uppheimsdal-Voss system (Ahlmann 1919).

Ornamented areas: horizontal ruling — northwestern basement gneisses; vertical ruling — sparagmitic rocks; oblique ruling — Cambro-Silurian schists; V-ornament — plutonic igneous rocks; circle ornament — allochthonous, Precambrian crystalline schists and plutonic rocks.

In the Møre-Jotunheimen region the oldest valley systems recognizable in different areas seem to constitute remnants of a radial drainage pattern (Zernitz 1932; Lobeck 1939; Strahler 1969). They are (Figs. 2 and 3): 1) the Sunndal-Drivdal-Gauldal system in Nordmøre and Trøndelag (Barrett 1900); 2) the Vermedal-Raumadal-Gudbrandsdal system in the Romsdal-Oppland area (Ahlmann 1919); 3) the Lærdal-Valdres system in the Sogn-Oppland area (Ahlmann 1919); and 4) the Stalheimsdal-Uppheimsdal-Voss system in the Sogn-Hordaland area (Ahlmann 1919).

These old drainage systems are apparently not of the subsequent type. The Sunndal-Drivdal-Gauldal system runs from the peripheral parts of the basal gneiss area of Møre, across several belts of rocks of varying resistance — base-

ment gneisses, Cambro-Silurian schists and sparagmites — and in a gentle and rather even curve through Cambro-Silurian schists and greenstones towards the Trondheimsfjord. On its way it passes between the two upland areas of Trollheimen and Dovrefjell-Snøhetta (Fig. 3). The Vermedal-Raumadal-Gudbrandsdal system likewise runs across bedrock of widely different resistance to erosion and passes between the upland areas of Rondane and Jotunheimen on its way towards the lowlands of East Norway, and eventually the Oslofjord. The two southern drainage systems are mere fragments of former river valleys; their upper reaches have been captured by the Sognefjord valley system and cannot be followed northwards into the uplands postulated to have existed in this region (Holtedahl 1953) prior to the formation, supposedly in the Tertiary, of the westward-draining, initial, dendritic valley system of the inner Sognefjord area. However, enough seems to be preserved of these two old valley systems to show that they, too, were non-subsequent (Fig. 2).

If a drainage pattern developed on a topographic relief as a result of differential erosion of rocks of varying resistance, with areas of resistant rocks forming uplands and easily eroded rocks forming lowlands, as has been postulated to explain the preserved upland areas of Norway (Holtedahl 1953), then the valleys of such a drainage pattern would be expected to be partly subsequent. This is not seen in the present instances. The radial pattern represented by the old valley systems seems, therefore, to be better explained by an originally consequent, radial drainage pattern of a regional, dome-shaped uplift. The passes between the mountain areas mentioned would then have formed old water gaps in the landscape of which the remnant, old valley systems were inherited, resequent valleys after the original, consequent drainage of the dome.

If the valley systems which guided the positions of the glacially eroded fjords and valleys in West Norway were originally conditioned by fluvial erosion after the Tertiary uplift, then possibly the upper, captured reaches of the older, regionally radiating valleys were elements of a pre-uplift landscape. Indirectly, this suggests that the assumed domal uplift may be pre-Tertiary in age. Rifting in connection with this uplift would lead to rapid erosion of the rift valley margins and to rapid sedimentation in the rift valley.

#### DOMAL UPLIFTS AND RIFTING

Schneider (1972) introduced the concept of sedimentary stages of development for ocean basins formed by rifting and subsequent ocean-floor spreading. The stages occur in the following sequence: 1) the rift valley stage; 2) the Red Sea stage; 3) the turbidite-fill stage; and 4) the deep-ocean current stage. Only the rift valley stage need concern us here. It is initiated by graben faulting caused by tensional rifting on thermally induced regional uplifts. In broad, regional uplifts several, near-parallel and competing rift systems may form, as for instance in the case of initial Triassic tension and rifting, with competing activities along the present Mid-Atlantic Ridge and the Triassic fault basin system along the east coast of North America from Alabama to Labrador (Schneider 1972).

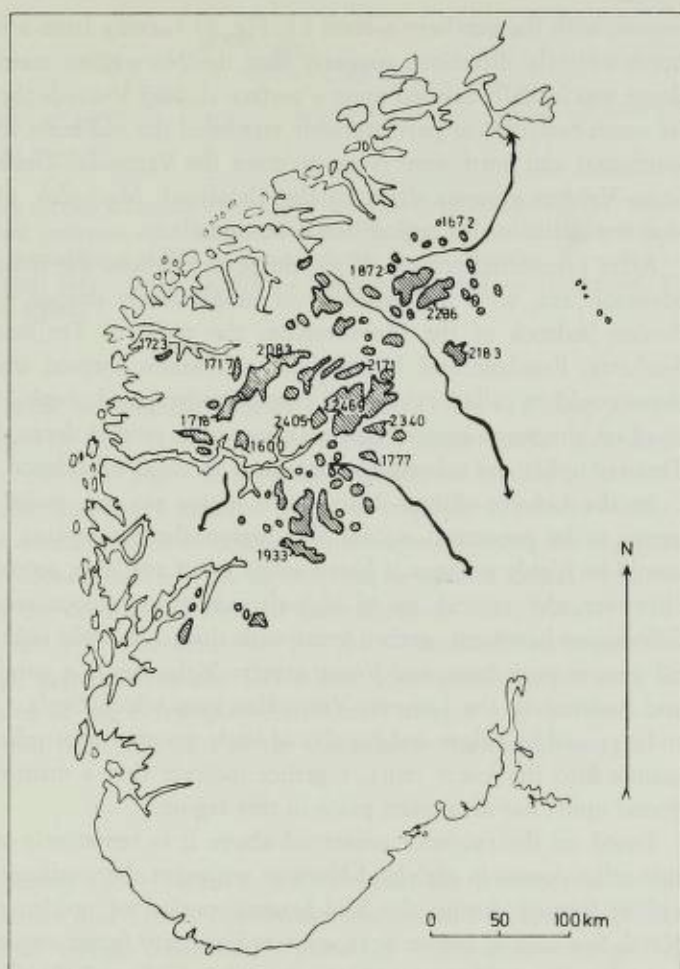


Fig. 3. Upland areas in west-central South Norway higher than 1500 m a.s.l. (lined ornament); summit levels in m a.s.l. Thick lines with arrow-head: old drainage systems (cf. Fig. 2), presumably representing an old, inherited, radial drainage pattern and running through wide, ancient water gaps, dissecting the upland area.

In the rift valley stage the crests of the rift valley walls become drainage divides: the regional drainage is down the gentle outward slopes of the uplift, or dome, away from the centre of uplift, and a local, internal drainage system forms within the rift valley system (Schneider 1972). In relation to the large-scale, crustal geometry and structure such a regional, external drainage must be classified as consequent, and the internal, graben drainage as obsequent. The steep fault scarps along the rift valleys will promote more vigorous erosion by the internal, obsequent drainage than by the external, consequent drainage, and the water divides will migrate away from the rift valleys. Thus the rift crests must be bevelled by erosion.

The old, disrupted, external drainage pattern in the Møre-Jotunheimen

region, with the northern system (1, Fig. 2) curving from a north-easterly to a north-westerly direction, suggests that the Norwegian mainland half of this dome was initially formed upon a surface sloping towards the WNW, and that its south-easternmost part probably straddled the old main watershed between south-east and north-west Norway, since the Vermedal-Gudbrandsdal and the Sogn-Valdres systems drain to the Oslofjord. Machaček (1908) considered that the uplift in this region had been domal.

After protracted erosion of the dome throughout the remaining part of the Mesozoic era, with the exposure of progressively deeper levels in the Caledonian bedrock of the Møre region, the resistant Trollheimen, Dovrefjell-Snøhetta, Rondane and Jotunheimen mountains formed what in a 'classical' dome could be called a dissected cuesta landscape (Lobeck 1939). This developed on the south-eastern half of a maturely eroded dome, later subjected to Tertiary uplift and subsequent, marginal flexural subsidence.

In the Lofoten-Troms-Norrbotten region no old, radial drainage pattern seems to be preserved, so for this region the assumption of a domal uplift would be highly tenuous if based solely upon available geomorphological data. However, the coincidence of high-altitude mountainous areas, deeply eroded Caledonian basement, graben areas with thick Mesozoic sediments, a continental margin re-entrant, and linear gravity highs running parallel to the margin and underneath the Lofoten-Vesterålen area which Sveta (1971) considered to be caused by ridges and cupolas of basic material protruding from the upper mantle into the lower crust, together indicate that a mantle plume-generated domal uplift has also taken place in this region.

Based on the evidence presented above it is tentatively suggested that the two relict domes in mainland Norway represent the south-eastern parts of two uplifts formed during the Mid-Jurassic period of uplifting recorded in the North Sea area in contemporaneous sedimentary facies sequences and regional unconformities (Howitt 1974; Sellwood & Hallam 1974; Ziegler 1975).

#### TERTIARY OBLIQUE UPLIFTS AND MARGINAL DOWNWARD

In the Early Tertiary renewed rifting — this time followed by the still continuing ocean floor spreading — took place along the north-western margin of Scandinavia. The oblique uplift associated with this rifting, and the later downwarping along the continental margin affected also the mainland remnants of the old domes. In the Møre-Jotunheimen area this may have produced the general profile indicated in Fig. 4, where the 'cuesta' of the original dome now forms the summit hump on the profile, while the more central part of the dome forms a gentle curve sloping down to the coast.

Downwarping of continental margins after the initial upwarps has been ascribed to increased sedimentary load along the margin (e.g. Walcott 1972), to vertical thermal contraction as the initial high heat flow regime moves away from the continental margin together with the mid-oceanic ridge (Sleep 1971, 1973), and to plastic flow of deep crustal material towards the newly created oceanic area (Bott 1973b). These hypotheses are not mutually exclusive. In a

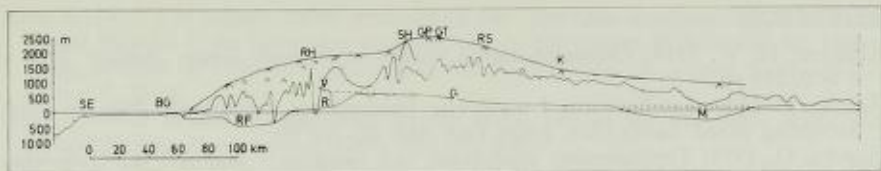


Fig. 4. NW-SE profile section across the Norwegian landmass from lake Mjøsa (M) to the Møre continental shelf (redrawn after Holtedahl 1960, Pl. 15): SE — Storegga; BG — Buagrunden; RF — Romsdalsfjord; RH — Romsdalshorn; V — Vermedal; R — Raumadal; G — Gudbrandsdal; SH — Snøhetta; GP — Galdhøpiggen; GT — Glittertind; RS — Rondslottet; K — Kvien.

continental split with an angular course, oceanward flow of deep crustal material as envisaged by Bott (1973b) could possibly cause smaller subsidence on the side of the re-entrant angle than on the opposite protruding side of the rift, because a smaller amount of material would be required to restore isostatic equilibrium in the smaller sector of oceanic lithosphere adjoining the marginal re-entrant. This could explain why no corresponding upland domal remnants are to be seen on the continental shelf of Greenland. In fact, Vann (1974) suggested in his pre-drift reconstruction for the Greenland/Norwegian Sea region that a large gap between the Greenland continental margin and the Lofoten-Troms area of the Norwegian continental margin may be explained by subsidence of that particular part of the Greenland continental margin.

## Conclusion

The evidence presented above seems to indicate that the conjunction within the Møre-Jotunheimen and Troms-Norrbotten regions and adjoining offshore areas of continental margin re-entrants, Mesozoic sedimentary troughs of probable rift origin, linear gravity highs and dissected upland areas of deeply eroded continental crust may be explained as a result of Mesozoic mantle plume activity near the present coast in the two regions. These mantle plumes generated domal uplifts and rifts, none of which seems to have evolved beyond the rifting stage. Much later, the early Tertiary rifting and ensuing ocean floor spreading in the Norwegian/Greenland Sea area are thought to have partly followed the older zones of crustal weakness, and thus to have produced the present continental margin with its two re-entrants along the Norwegian coast. The inferred Mesozoic events may be regarded as a northern extension of pre-splitting tectonic activity along the present North American and north-west European Atlantic margins.

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