THE RELATION OF JOINT PATTERNS TO THE FORMATION OF FJORDS IN WESTERN NORWAY*

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The 'fissure' fjords of the western coast of Norway are north-south-oriented tributary fjords to the more prominent east-west-trending 'strike' fjords, and their orientation has been previously attributed to Caledonian or Svalbardian structural control. A detailed study of joint patterns in Devonian and older rocks of the Solund and Buelandet-Værlandet districts, which are located adjacent to the mouth of Sognefjorden, indicates that the orientation of the 'fissure' fjords is controlled by a prominent set of north-south-oriented joints. This joint set clearly cuts across earlier Caledonian and Svalbardian structures and is considered in this report to be of Tertiary age, related to the uplift and eastward tilting of the Scandinavian landmass. The joint set is parallel to and probably related to the Norwegian Channel, an offshore linear depression of Tertiary origin. The 'fissure' fjords were cut by Pleistocene tributary glaciers flowing in valleys eroded parallel to these major north-south joints. The 'strike' fjords follow older Caledonian and Svalbardian structural elements.

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The genesis of the spectacular fjords of western Norway has been the subject of numerous studies by geographers and geologists for the past one hundred years. Recent geophysical and oceanographic data both from within the fjords and from offshore areas have considerably influenced long-held suppositions regarding fjord origins (Hinz 1968, Talwani 1971). In addition to these data, recent geologic and geomorphic investigations in the coastal regions of western Norway have contributed to the development of modern concepts about the formation of fjords. The writer's interest in the fjords of western Norway originated from structural studies, particularly of joint patterns, made in the Solund and Buelandet-Værlandet Devonian districts (Fig. 1). Earlier ideas about fjord origins and the tectonic framework of fjord development had been handicapped by a lack of detailed geologic studies of the tectonic history of western Norway, particularly in the Sognefjorden-Nordfjord region.

Western Norway is characterized by two distinct fjord sets:

'Strike' fjords, which are oriented east-west (perpendicular to the coastline) and generally parallel to Caledonian structural trends.

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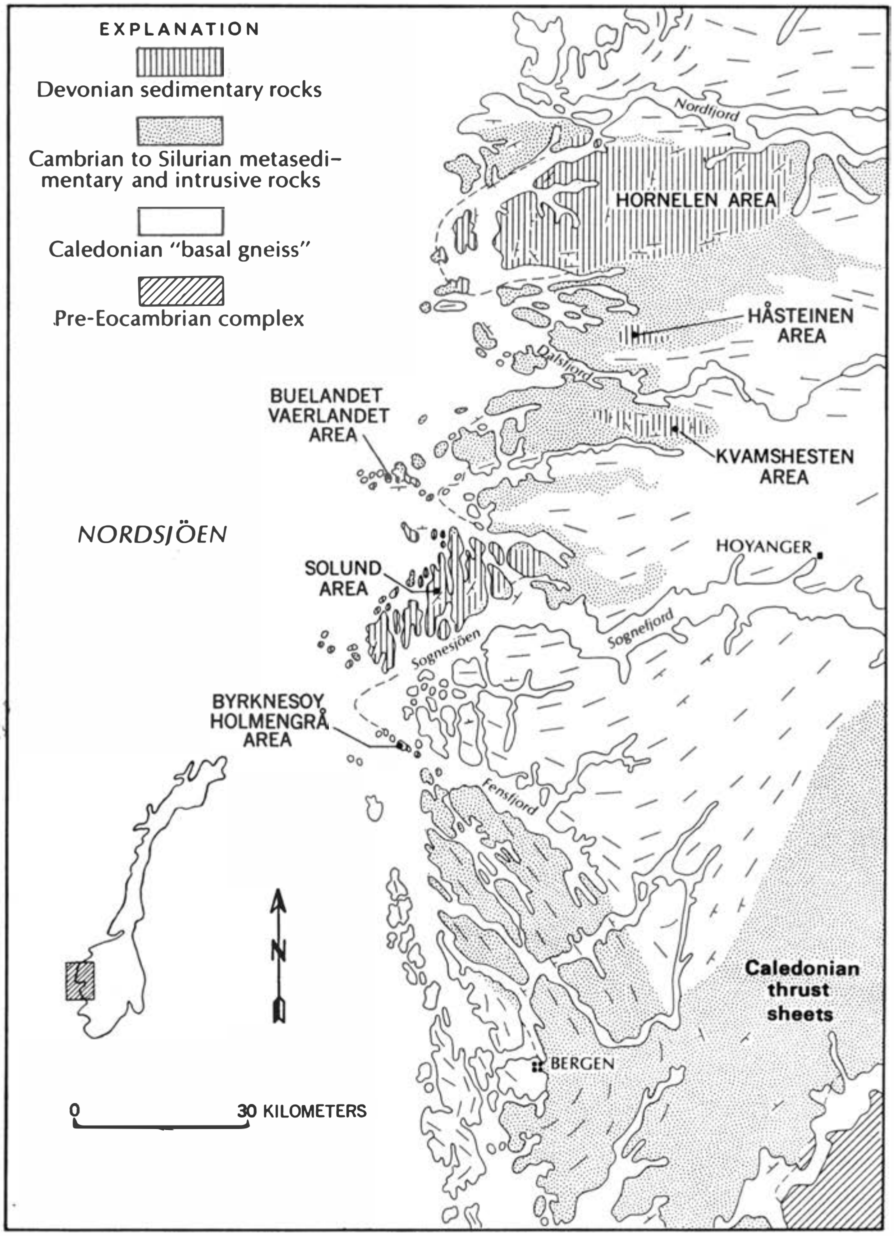

Fig. 1. Geologic map of western Norway (modified from O. Holtedahl & J. A. Dons 1960).

'Fissure' fjords, which are oriented north-south (parallel to the coastline) and generally cut across Caledonian structural trends.

Sognefjorden, Dalsfjorden, and Nordfjord are examples of 'strike' fjords (Fig. 1), and Straumsfjorden, Hagefjorden, Nesefjorden, Krakhellesundet and Storakersundet are examples of 'fissure' fjords (Fig. 2). The larger and longer 'strike' fjords extend long distances into central Norway (as much as

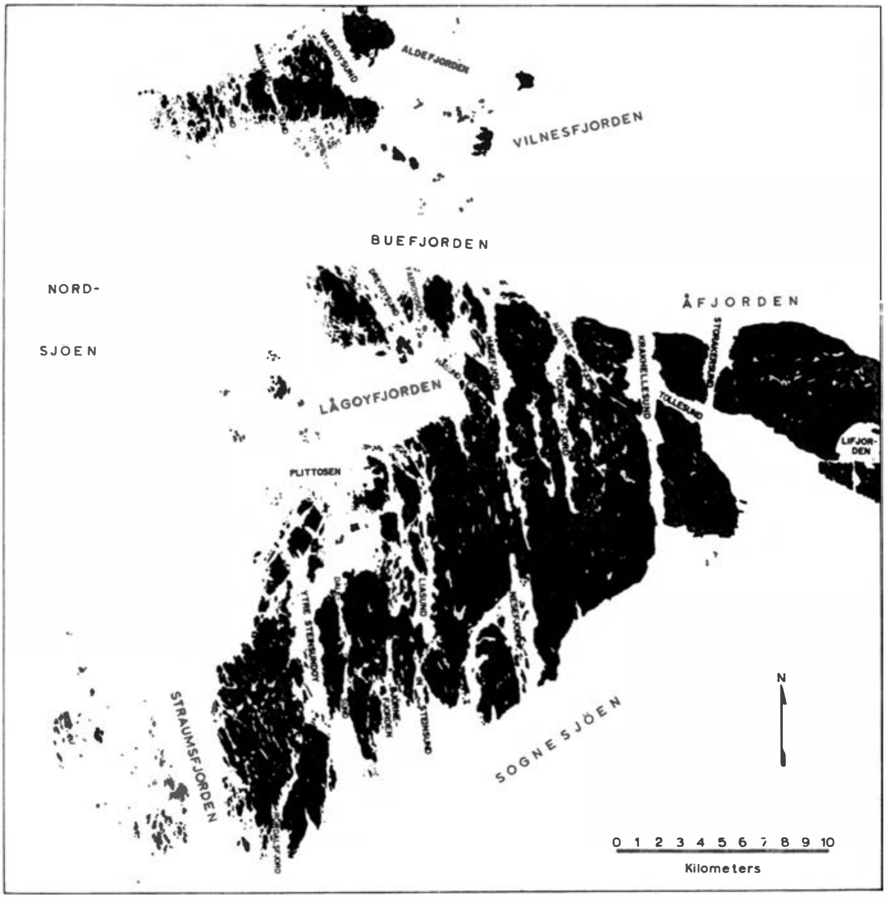

Fig. 2. Outline map of the Solund and Buelandet-Værlandet districts.

170 km), attain great depths (a maximum of 1308 m), are surrounded by high, steep bounding walls (up to 1600 m in elevation), and penetrate many different types of rock. The 'fissure' fjords are most prominent along the coast, particularly in the Solund and Buelandet-Værlandet island groups, where they dissect resistant Devonian conglomerates and sandstones. In contrast, these fjords are typically narrower, more discontinuous, not nearly as deep, and not as steep or high-walled as the 'strike' fjords. The problem presented by this systematic fjord pattern, aside from the mechanics of eroding these features, is the relation of the fjords to the Caledonian, Svalbardian and Tertiary tectonic episodes in western Norway.

The Sognefjorden-Nordfjord region is underlain by a suite of highly metamorphosed rocks loosely grouped together under the term 'basal gneiss' (Fig. 1). The 'basal gneiss' is thought to consist of Precambrian to Silurian rocks that were metamorphosed and structurally uplifted during the Caledonian orogeny (N.-H. Kolderup 1931b, 1960). Cropping out within this group of gneisses, amphibolites, and eclogites are lower grade phyllites,

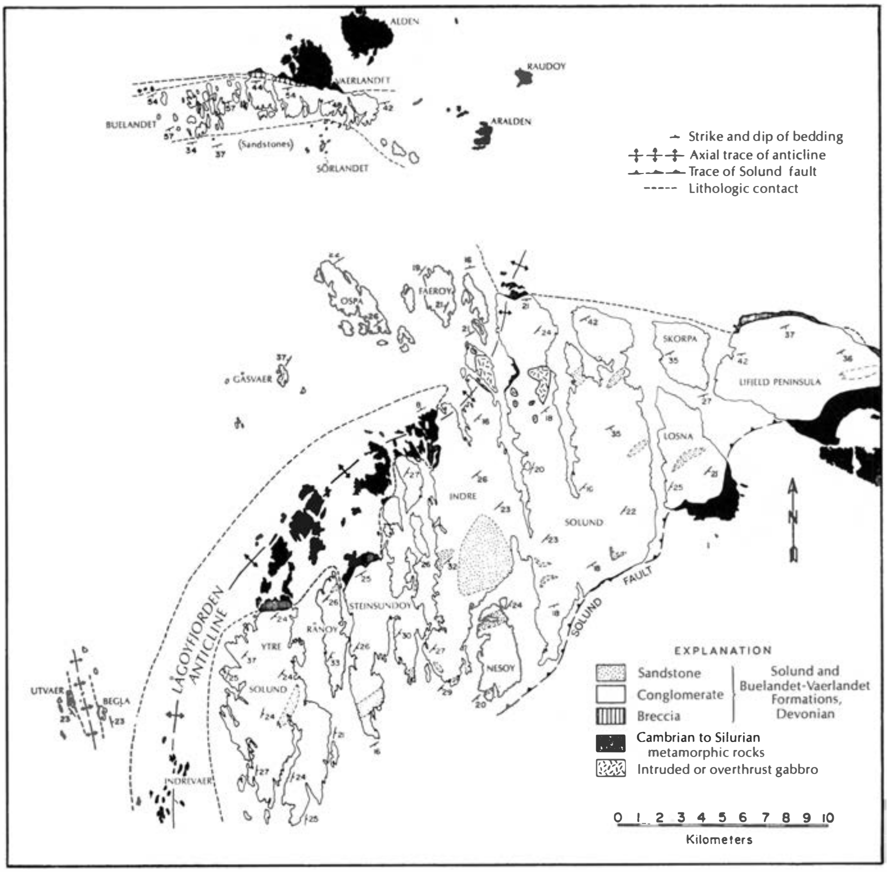

Fig. 3. Geologic map of the Solund and Buelandet-Værlandet districts.

schists, quartzites, metaconglomerates, metabasalts, and metagraywackes that were also affected by the Caledonian orogeny. Because of local conditions of metamorphism or higher stratigraphic position (i.e. shallower burial), these rocks have not been as highly metamorphosed as the 'basal gneiss'.

Breccias, conglomerates and sandstones of Early and Middle Devonian age were deposited in six intramontane basins after the uplift of the Caledonian mountains in western Norway at the end of the Silurian. The Devonian rocks, being more resistant to erosion, presently stand topographically higher than the underlying metamorphic rocks which were the original source rocks for the Devonian sediments. Recent studies suggest that the Devonian rocks represent faulted graben and half-graben basins (Bryhni 1964a, 1964b, Nilsen 1969a, 1969b), an interpretation that contradicts the earlier suggestions by N.-H. Kolderup (1928, 1931b) that the Devonian basins were synclinal and perched on broader underlying synclines formed by the older metamorphic rocks. The Solund district is clearly anticlinal (Fig. 3). The fjords generally cut indiscriminately through the 'basal gneiss', schist, and Devonian rocks.

Joint patterns

Background

One of the most prominent characteristics of the Devonian rocks along the west coast of Norway is a very well-developed system of jointing. These joints are particularly prominent in the Solund and Buelandet-Værlandet Devonian districts, the westernmost Devonian districts (Fig. 1). The joints are commonly open, very straight, and vertical, and many joint surfaces form very imposing and steep cliffs (Nilsen 1969a). Several joint sets are common in any area, and the joint surfaces control the location of prominent topographic features more than do bedding or fault surfaces. Individual joints may be traced for many kilometers, and they commonly cut across many topographic features and different rock types, generally maintaining remarkably straight and nearly vertical orientations.

Joint patterns were studied in both the Devonian and pre-Devonian rocks,

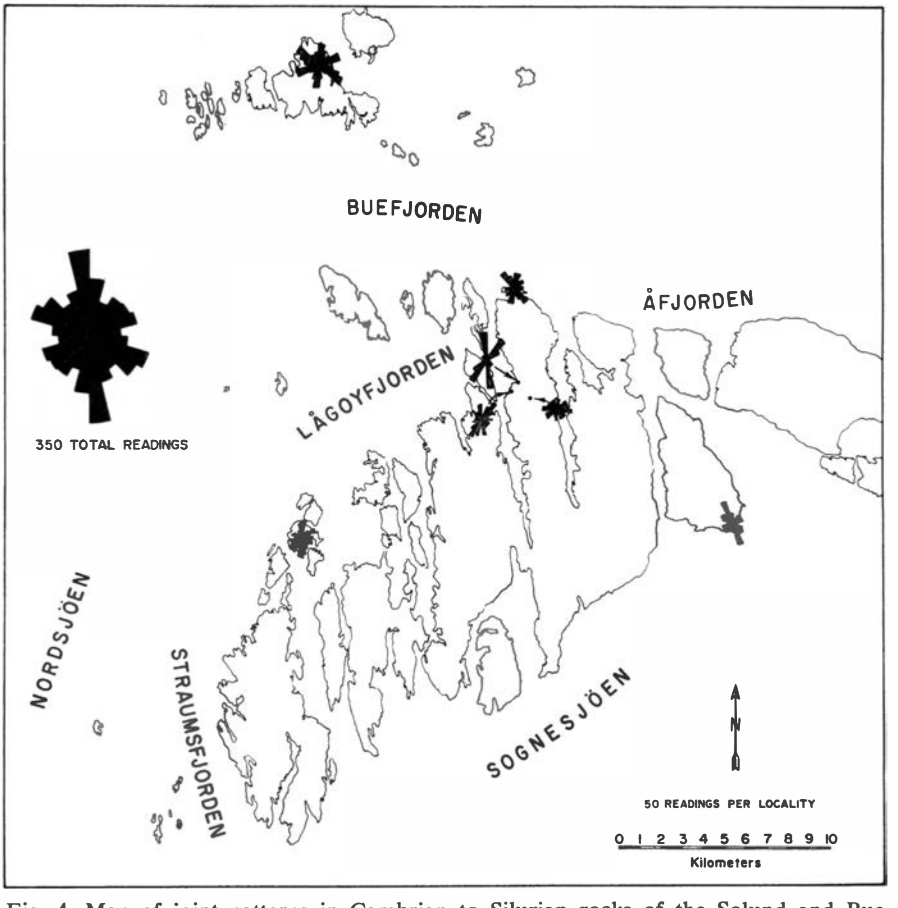

Fig. 4. Map of joint patterns in Cambrian to Silurian rocks of the Solund and Buelandet-Værlandet districts.

and a total of 2500 joint orientations were measured at randomly selected localities that generally provided good geographical coverage of the study area. The strike and dip of 50 joints were measured randomly at each locality. Because the overwhelming majority of dip amounts are close to 90°, the joint orientations can be conveniently illustrated by simply plotting strike directions on rose diagrams.

Cambrian to Silurian rocks

Joint patterns in Cambrian to Silurian rocks of the Solund and Buelandet-Værlandet districts are shown in Fig. 4. The joint pattern generally shows three prominent orientations, in decreasing order of frequency: north-south (345°–360°), northeast (30°–45°), and northwest (300°–315°) (Table 1). The least number of joints are found in approximately an east-west orientation. However, there is considerable scatter in the joint orientations, and only 350 measurements were taken. Joints in the Cambrian to Silurian rocks are not as well developed as in overlying Devonian rocks and are more closely spaced, less straight, less vertical, and in general have more complex patterns. The joint measurements include 50 measurements from within a gabbro body in northern Indre Solund (Fig. 3) that may intrude the Devonian sedimentary rocks and therefore may be of younger age than the other rocks sampled.

Devonian rocks

Joint patterns in Devonian rocks are shown in Fig. 5 and summarized in Table 1. The joint pattern again shows three prominent orientations, in decreasing order of frequency: north-south (345°–360°), northwest (285°–300°), and northeast (60°–75°). The north-south orientation is by far the most prominent over the entire area, and Fig. 5 indicates that in any particular area, the joints tend to be remarkably constant in orientation, with very little scatter. The least number of joint orientations is again in the east-west direction.

Table 1. Distribution of joint orientations of Cambrian to Silurian, and Devonian rocks, Solund and Buelandet-Værlandet districts.

Strike directions	270-285	285-300	300-315	315-330	330-345	345-360	0-15	15-30	30-45	45-60	60-75	75-90	Total
Number of joints, Cambrian to Silurian rocks	12	22	26	23	26	37	26	27	34	31	20	16	350
Number of joints, Devonian rocks	139	225	201	138	170	315	205	125	166	170	182	114	2,150

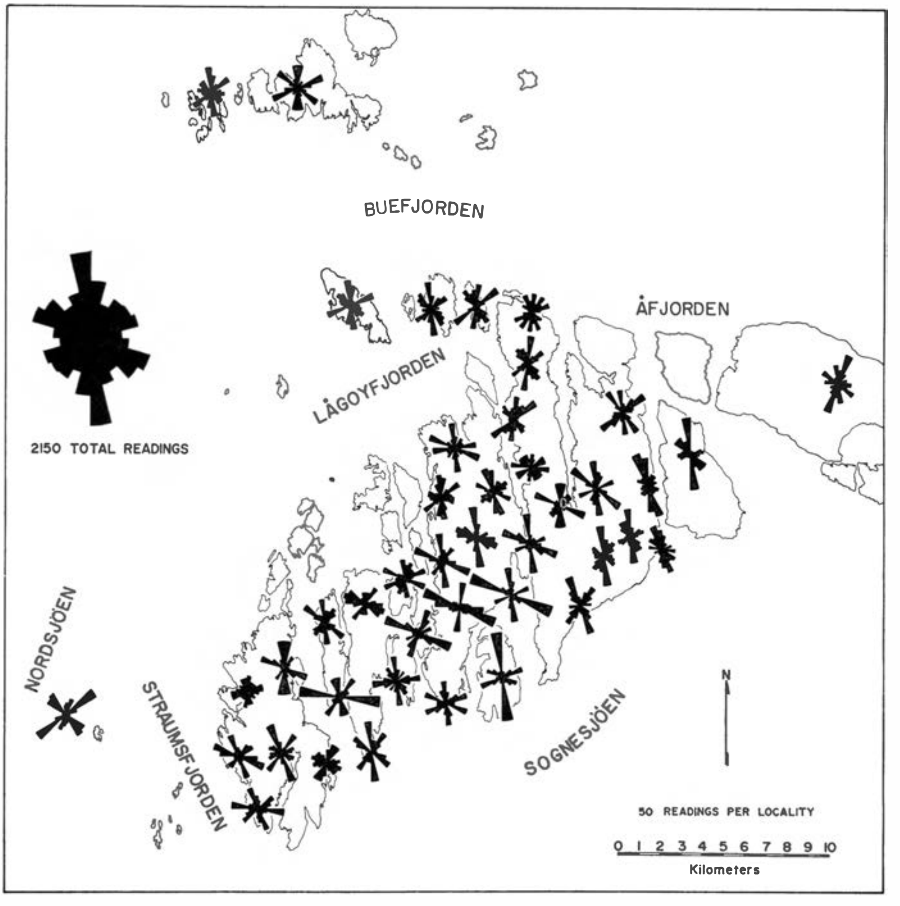

Fig. 5. Map of joint patterns in Devonian rocks of the Solund and Buelandet-Værlandet districts.

Relation to geography

Striking similarities exist between the geographic orientation of islands, rivers, lakes, fjords, and coastlines to the three major joint sets, as seen from a comparison of Figs. 2 and 5. The dominant topographic control in the Solund and Buelandet-Værlandet districts is clearly joint orientations. The north-south-oriented 'fissure' fjords are parallel to the most prominent joint pattern (345°–360°). Other fjords such as Tollesund, Håsundet, and Austrefjorden are parallel to the northwest-trending joint set (Fig. 2). Numerous northeast-trending features are parallel to the northeast-trending joint set. In fact, the relative influence of these topographic orientations is similar to the frequency of occurrence of the joint sets; that is, the north-south topography is most prominent, as is the north-south joint set, with the northwest orientation ranking second and the northeast third.

Summary of the tectonic history of western Norway

Caledonian structural trends

Little is known of the distribution or composition of Precambrian rocks in western Norway; undoubtedly, they were affected by the Caledonian orogeny and are presently incorporated within the 'basal gneiss'. Examination of folding styles in the Cambrian to Silurian rocks indicates the presence of several orogenic episodes (F. J. Skjerlie, pers. comm. 1965). All were probably produced during the Caledonian orogeny, which is now thought to have extended from late Precambrian through Devonian time in northwestern Europe. In fact, modern usage of the term would include the Svalbardian (Devonian) disturbance in western Norway as a late feature of the Caledonian orogeny. In this report, however, the Devonian events will be considered separately from earlier Caledonian events.

The oldest folds in rocks deformed during the Caledonian orogeny are the tightest and trend east-west. A second set of folds has two perpendicular axial trends, northwest-southeast and northeast-southwest. The dominant trend is northeast-southwest, however, and this structural direction is the dominant one in the Scandinavian Caledonides. A third set of folds again trends east-west and is the most open in style. These folds may have resulted from Devonian tectonism, for folds of this type are also found in the overlying Devonian strata; however, this relation has not been conclusively established.

Svalbardian structural trends

Two phases of Devonian tectonic activity are evident in western Norway:

The formation of grabens and half-grabens, resulting in structural basins bounded by faults that trend east-west or northeast-southwest, parallel to the older Caledonian structural trends.

An episode of folding and faulting primarily along east-west axes, but which also thrust Devonian rocks to the east and southeast over basement rocks (Nilsen 1971). The initial phase provided basins in which Devonian sediments were deposited, and structural uplift of the basin margins continued to take place during sedimentation. The second phase resulted in the deformation and uplift of the basin deposits. Fold axes and faults in Devonian rocks trend either east-west or northeast-southwest, parallel to older Caledonian trends. The folds and faults penetrate to the underlying older rocks and may be equivalent to the third fold system within the older rocks.

Possible Permian structures

No clear evidence has been presented to prove that the Permian tectonism that took place in the Oslo area affected western Norway. However, this does not preclude the possibility that some structures in western Norway are of Permian or Mesozoic age. However, inasmuch as Devonian rocks are the youngest to crop out in western Norway, interpretation of post-Devonian tectonic events is difficult.

Cenozoic tectonic activity

The entire Scandinavian landmass was uplifted and tilted eastward during the Cenozoic Era, so that the highest elevations are found in the western part of Norway, and lower elevations are found eastward in Sweden and Finland (Holtedahl, H. 1959, 1960, Holtedahl, O. 1960, Holtedahl, O. & Holtedahl, H. 1961). The Norwegian channel, a long, linear submarine depression, which is as much as 700 m deep and 900 km long, is present in the continental shelf south and west of Norway and generally trends parallel to the coastline. It is thought to be a graben and the locus of Cenozoic faulting along which the Scandinavian landmass to the east was uplifted (Holtedahl, O. 1960). This offshore fault zone has truncated westward-trending submarine valleys and has apparently been active into the Quaternary Period; uplift has continued into the Holocene partly as a result of post-glacial unloading.

The times of formation of the channel and the initiation of uplift are not known, but movements probably occurred throughout the Cenozoic Era at the same time as the North Atlantic was being formed by sea-floor spreading (Pitman & Talwani 1972). Recent studies of the ocean floor indicate that the Norwegian Sea initially opened in early Tertiary time (Talwani 1971). Unfortunately, marine Tertiary deposits are absent in Norway, so little is known about this period. Scandinavia was most likely a rising landmass during most of the Tertiary Period. The uplift and tilting were primarily extensional in nature, without any accompanying folding or thrusting.

Summary of tectonic history

Caledonian and Svalbardian tectonism occurred repeatedly along similar structural trends – primarily east-west and northeast-southwest. The orientations of the Svalbardian structures were apparently controlled by pre-existing structural trends, and the orientation of the Caledonian geosyncline to the Fenno-Scandinavian shield undoubtedly was the controlling factor. Tertiary tectonism was not of the orogenic type but consisted primarily of the vertical uplift and eastward tilting of the entire Scandinavian landmass along north-south-oriented submarine fault zones located west of the Norwegian coastline.

Structural control of fjord orientations

N.-H. Kolderup (1931a) summarized earlier proposals regarding fjord origins, most of which suggested that the 'strike' fjords were parallel to Caledonian structural trends and that glaciers following previously formed river channels cut the fjords along lines of structural and lithologic weakness. Kolderup (1931a, 1934a, 1934b) further noted that most of the 'strike' fjords on the west coast cut through less resistant Cambrian to Silurian phyllites and schists, which he thought were exposed in the crests of anticlines located adjacent to synclines that contained more resistant Devonian strata. He ascribed the origin of the 'fissure' fjords to erosion by smaller glaciers flowing north and south as tributaries to the larger glaciers in the 'strike' fjords; these glaciers occupied old tributary stream valleys. The north-south-trending joint directions followed by the glaciers cutting the 'fissure' fjords were thought to be post-Caledonian, Permian, or Tertiary in age. Faulting was thought to have taken place along some of these joints (C. F. Kolderup 1926, N.-H. Kolderup 1931a), but this was subsequently questioned by Nilsen (1969a).

H. Holtedahl (1967) concluded from geomorphic and oceanographic studies of the 'strike' fjords that glacial erosion, related to ice thickness, was primarily responsible for cutting the fjords. He suggested that subglacial fluvial erosion was also a contributing cause, while turbidity currents in the fjords have had only a very slight erosive effect. Tectonic patterns resulting from Caledonian, Svalbardian and possibly Permian disturbances were thought to be the controlling factors in fjord orientation, with the Cenozoic uplift of Scandinavia having had some influence.

The prominent north-south-trending joint system is not clearly related structurally either to Caledonian or Svalbardian tectonic events or to structural trends. The north-south system appears to be superimposed upon the pre-existing Caledonian and Svalbardian structures. The Cambrian to Silurian rocks appear to have a somewhat mixed pattern of joint orientations upon which the prominent north-south set has been superimposed. Devonian rocks in the Solund area are folded into a northeast-oriented anticlinal structure, but the north-south joint set clearly intersects this feature without being affected by it in any way. These relations suggest that the most prominent joint system is post-Svalbardian in age and is most probably Tertiary. The joint set is parallel to the Norwegian Channel, a structural feature of Tertiary age. The fact that this joint set is so prominently developed in the Solund and Buelandet-Værlandet islands suggests that the joints may be more strongly developed to the west, closer to the Channel.

The entire joint system, characterized by a major north-south-oriented set with an associated northeast- and northwest-oriented conjugate pair, may have been formed by east-west extension related to the vertical uplift and tilting of Scandinavia. The major joint set may represent tension joints formed perpendicular to the direction of extension, and the conjugate pair may be shear joints. As would be expected under these conditions, little jointing in the east-west direction has been found. The underlying cause for this extension may have been the spreading sea floor in the North Atlantic region during the Tertiary Period, with the direction of spreading being east-west (Pitman & Talwani 1972).

Bostrom (1970) noted similar extensional features parallel to the coastline in the fjordlands of British Columbia and Chile. He suggested that along these continental edges, which had been rifted apart by sea-floor spreading in the Pacific, relaxational extension had occurred that resulted in the collapse of the continental margin and oceanward movement of the broken fragments. Accompanying glaciation concentrated along the fracture zones resulted in a geography with very strongly marked linear elements; in fact, glacial loading might have contributed to the collapse of the margin. Bostrom further suggested that the Norwegian and Greenland fjord systems had originated in a similar way. The joint systems noted in this report suggest that he may be correct, and the Norwegian Channel may be a major fracture zone along which the continental edge has collapsed. Eastward tilting of the continental landmass may have enabled large crustal fragments to break off along the western edge. The joints may have opened into the present system of large, open, linear valleys, and troughs in part coevally with glacial erosion.

The 'fissure' fjords along the west coast, then, are related to this Tertiary joint system: the tributary glaciers followed previously eroded stream valleys or syntectonically opening linear depressions that were oriented parallel to the major joint set. The 'strike' fjords follow older Caledonian or Svalbardian structural trends, such as the foliation orientation in the 'basal gneiss', lithologic contacts, faults, or joints (Fig. 1). This latter relation is clear in the Solund area, where the Sognesjöen veers southwestward, following the southeastern edge of the Solund Devonian district, where it is probably cut into less resistant Cambrian to Silurian phyllites and schists (Fig. 3).

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REFERENCES

Bostrom, R. C. 1970: Relationship of the world rift system to the fiord regions in Chile and British Columbia. *Modern Geology 1*, no. 4, pp. 261–273.

Bryhni, I. 1964a: Relasjonen mellom senkaledonsk tektonikk og sedimentasjon ved Hornelens og Håsteinens devon. *Norges geol. undersøkelse 223*, pp. 10–25.

Bryhni, I. 1964b: Migrating basins on the Old Red Continent. *Nature 202*, pp. 384–385.

Hinz, K. 1968: A contribution to the geology of the North Sea according to geophysical investigations by the Geological Survey of the German Federal Republic. *In* Geology of shelf seas. *Inter-University Geol. Cong., 14th. Proc.* Oliver & Boyd, Edinburgh and London, pp. 55–71.

Holtedahl, H. 1959: Some remarks on geomorphology of continental shelves off Norway, Labrador, and southeast Alaska. *Jour. Geology 66*, pp. 461–471.

Holtedahl, H. 1960: Mountain, fjord, strandflat; geomorphology and general geology of parts of western Norway. *Int. Geol. Congr. 21, Guide to excursions A6 and C3.* Oslo.

Holtedahl, H. 1967: Notes on the formation of fjords and fjord-valleys. *Geografiska Annaler, 49, ser. A,* pp. 188–203.

Holtedahl, O. 1960: On supposed marginal faults and the oblique uplift of the land mass in Cenozoic time. *In* Geology of Norway, *Norges geol. undersøkelse 208,* pp. 351–357.
Holtedahl, O. & Dons, J. A. 1960: Geological map of Norway (bedrock). *Norges geol. undersøkelse 208.*
Holtedahl, O. & Holtedahl, H. 1961: On 'Marginal Channels' along continental borders and the problem of their origin. *Geol. Inst. Uppsala Bull. 40,* pp. 183–187.
Kolderup, C. F. 1926: Vulkansk virksomhet og indpresning av ældre bergarter, Vestlandets devon. *Naturen,* pp. 129–142.
Kolderup, N.-H. 1928: Fjellbygningen i kystströket mellom Nordfjord og Sognefjord. *Bergens Mus. Aarbok 1928, Naturvidensk. Række no. 1,* pp. 1–222.
Kolderup N.-H. 1931a: Vestnorske fjorders avhengighet av kaledonisk tektonikk. *Norsk geol. tidsskr. 12,* pp. 441–458.
Kolderup, N.-H. 1931b: Oversikt over den kaledoniske fjellkjede på Vestlandet. *Bergens Mus. Aarbok 1931, Naturvidensk. Række no. 1,* pp. 1–43.
Kolderup, N.-H. 1934a: Fjordenes retningslinjer og fjellbygningen på Vestlandet. *Naturen,* pp. 367–378.
Kolderup, N.-H. 1934b: The Norwegian fjords and their relation to tectonics. *Fifth Pacific Sci. Cong. Proc., Canada,* 1933, pp. 713–718.
Kolderup, N.-H. 1960: The relationship between Cambro-Silurian schists and the gneiss complex in the deep-Caledonides of Sogn and Fjordane, west Norway. *XXI Intern. Geol. Cong., Guide to Excursions no. A5 and C2,* 32 pp.
Nilsen, T. H. 1969a: The relationship of sedimentation to tectonics in the Solund Devonian district of southwestern Norway. *Norges geol. undersøkelse 259,* 106 pp.
Nilsen, T. H. 1969b: Old Red sedimentation in the Buelandet-Værlandet Devonian district, western Norway. *Sedimentology 3,* no. 1, pp. 35–57.
Nilsen, T. H. 1971: Devonian (Old Red Sandstone) sedimentation and tectonics of Norway. *Am. Assoc. Petroleum Geologists Bull. 54,* no. 12, pp. 2498–2499.
Pitman, W. C. III, & Talwani, M. 1972: Sea floor spreading in the North Atlantic. *Geol. Soc. America Bull. 83,* no. 3, pp. 619–646.
Talwani, M. 1971: The continental margin off Norway and the evolution of the Norwegian Sea. *Geol. Soc. America Abstracts with Programs, 3,* no. 7, p. 728.