Tectonostratigraphic position of the rocks in the western extreme of the Major Bergen Arc (Fanafjell Nappe), West Norway

HAAKON FOSSEN & SVEIN ERIK INGDAHL

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Rocks of the 'Fanafjell Nappe' (Sturt & Thon 1978) in the Bergen Arcs have been studied. The Krossnes Granite, which dominates the area, intrudes rocks of the Major Bergen Arc, and is separated from the Anorthosite Complex by a broad zone of mylonites. The Krossnes Granite is thus interpreted as one of several syn-tectonic granitoids within the Scandinavian Caledonides, and not as a separate nappe.

H. Fossen, geologisk inst., Univ. i Bergen, Allegt. 41, N-5000 Bergen. Present address: Statoil, postboks 1212, N-5001 Bergen, Norway. S. E. Ingdahl, Statoil, postboks 1212, N-5001 Bergen, Norway

The Krossnes Granite (Kolderup & Kolderup 1940), also termed the Fana Granite (Brueckner 1972), occupies the southwestern part of the Bergen Arc System (Fig. 1). The granite is located at the contact between the Major Bergen Arc and the Anorthosite Complex. The present authors believe that it forms part of the Major Bergen Arc. With the exception of Sharma & Sturt (1977), no detailed investigations have been carried out in this area. Brueckner (1972) calculated a Rb/Sr 'age' of the granite about 440 ± 50 My, supporting Holtedahl & Dons (1960) and Kvale's (1960) interpretation of this granite as being Caledonian.

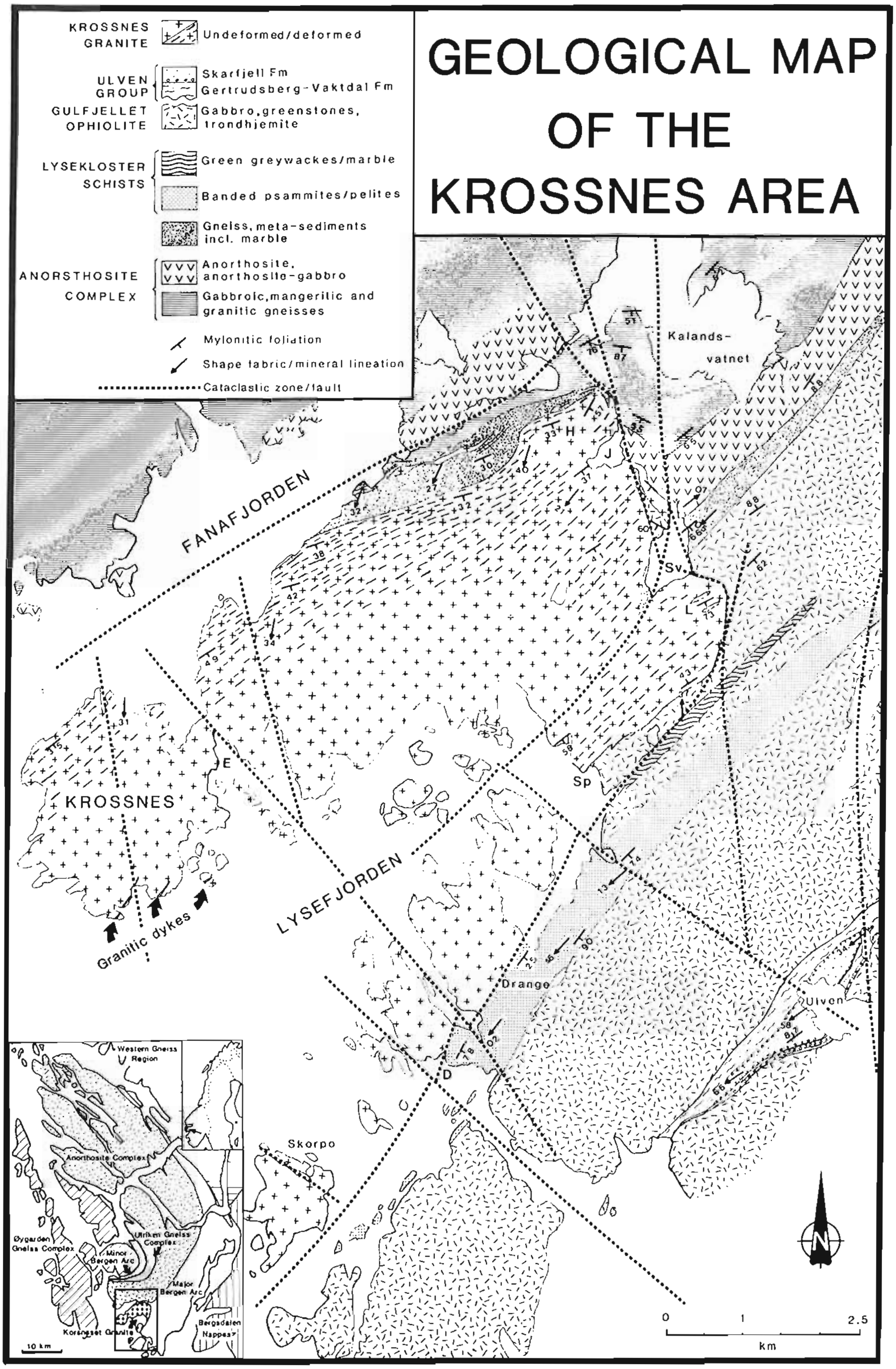
A tentative interpretation of the tectono-stratigraphy of the Bergen Arcs has been presented by Sturt & Thon (1978). The Precambrian Anorthosite Complex and the Ulriken Gneiss Complex were claimed to overlie rocks of the Minor and Major Bergen Arcs, being separated by disjunctive thrust contacts. The Krossnes Granite, together with minor metasediments, was included in the 'Fanafjell Nappe', representing the highest tectonic unit in the Bergen nappe sequence. Thon (1985) also claimed that the contact between the Gulfjellet Ophiolite Complex (GOC) and the Krossnes Granite is a fault. However, evidence has not been advanced in support of these interpretations, and a re-examination of the area by the present authors has indicated that the earlier interpretation by Sturt & Thon (1978) should be modified. A brief description of the Fana-Krossnes area will be given as a basis for the alternative interpretation.

The Krossnes Granite

The Krossnes Granite is coarse-grained (Fig. 2a) and contains potassium-feldspar megacrysts which often give the granite a reddish colour. The rectangular feldspar crystals are usually about 1 cm in diameter and commonly have exsolved plagioclase, forming string-perthites and fleck-perthites. Myrmekite occurs along the margins of some grains, especially where deformation has taken place. In addition the granite contains quartz, mantled plagioclase (albite), opaques, epidote and small amounts of biotite, apatite, sphene and zircon. Epidote is normally a secondary mineral, related to late fracturing and jointing.

The granite can be divided into two phases of different grain-size. A coarse-grained granite dominates, and is commonly veined or cut by a more fine-grained granite of similar composition. This aplitic phase has brecciated the granite in places, though also aplitic dykes are faulted and fractured by probably syn-intrusive deformation.

The average grain-size of the pluton decreases slightly towards the contacts to the north and the east. The granite is generally of true granitic composition, but is locally granodioritic along its margins. The syenitic variety described by Kolderup & Kolderup (1940) has not been found.


GEOLOGICAL MAP
OF THE
KROSSNES AREA
KROSSNES GRANITE
Undeformed/deformed
ULVEN GROUP
Skarfjell Fm
Gertrudsberg-Vaktdal Fm
GULFJELLET OPHIOLITE
Gabbro, greenstones, trondhjemite
LYSEKLOSTER SCHISTS
Green greywackes/marble
Banded psammites/pelites
Gneiss, meta-sediments incl. marble
ANORSTHOSITE COMPLEX
Anorthosite, anorthosite-gabbro
Gabbroic, mangeritic and granitic gneisses
Mylonitic foliation
Shape fabric/mineral lineation
Cataclastic zone/fault
Kalands-
vatnet
FANAFJORDEN
LYSEFJORDEN
KROSSNES
Granitic dykes
Drange
Ulven
Skorpo
Sv
Sp
H
J
L
E
D
0
1
2.5
km
Western Gneiss Region
Anorthosite Complex
Øygarden Gneiss Complex
Ulriken Gneiss Complex
Minor Bergen Arc
Major Bergen Arc
Krossnes Granite
Bergsdalen Nappes?
10 km

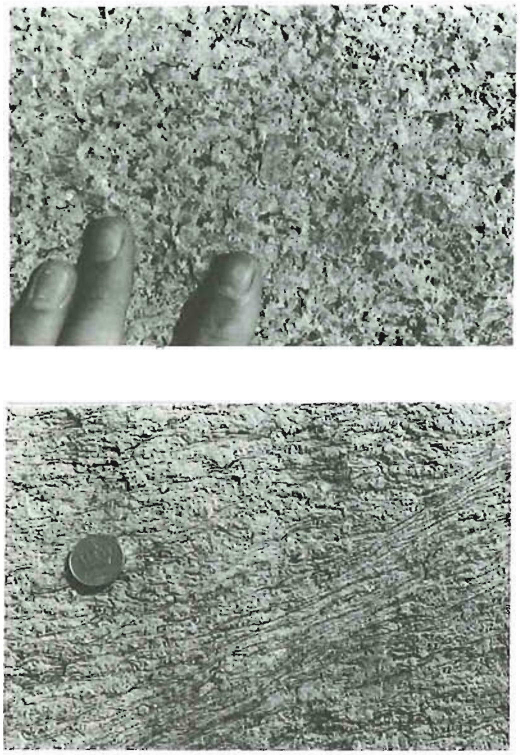


Fig. 2.(a) The Krossnes Granite undeformed. Potassium feldspars of centimetre size are seen. (b) Deformed Krossnes Granite. Note shear-bands characteristic for S-C mylonites. Locality at Krossneset. (UTM 294–6682).

Fig. 3. Large xenoliths of rocks of the Gulfjellet Ophiolite Complex broken up into smaller xenoliths. Locality at Skorpo. (UTM 295–6675.5).

Xenoliths are common in the Krossnes Granite (Kolderup & Kolderup 1940). The xenoliths are biotite-rich rocks and amphibolites which may be correlated with rocks of the GOC and metasediments of the Major Bergen Arc. There are in addition strongly-foliated, quartzitic to arkositic xenoliths with strong planar fabrics. These rocks resemble the mylonites along the northern boundary of the Krossnes Granite and along the GOC. The xenoliths may form large blocks up to tens of metres long, but generally they are only a few centimetres across. The xenoliths are concentrated in zones, partly due to disruption of larger xenoliths. The latter can be demonstrated on the southern part of the island of Skorpo (Fig. 3). In areas where the granite is only slightly deformed, it can be shown that the granite has enveloped foliated xenoliths.

Fig. 1. Geological map of the Krossnes area. D = Danielsviken, E = Eidsvågen, H = Hamresåta, J = Jordevatnet, Sp = Sperreviken, Sv = Svartevatnet, L = Lysehornet.

The xenoliths show all stages of assimilation. Some xenoliths have sharp outlines while nearly completely assimilated xenoliths occur as dark shadows in the coarse-grained granite. The latter probably lead Kolderup & Kolderup (1940) to suggest that more basic parts of the intrusion are preserved as xenoliths within the granite.

Porphyroblasts of potassium-feldspar occur within many xenoliths due to metasomatism. The xenoliths show a preferred orientation subparallel to the regional foliation (NE-SW with dips towards the south).

Dykes

A few dykes cut the granite in the westernmost part (Fig. 1). Grey, granitic dykes with chilled margins occur at Krossneset. The dykes are oriented NE-SW and have steep, northerly dips. As these dykes are only found at the westernmost part of the granite, they are likely to represent satellite dykes of the Sunnhordland Batholite to the SW. Two lamprophyric dykes are present near Eidsvågen (Fig. 1). Xenoliths of the granite are enclosed within the dykes. The lamprophyric dykes are greyish-green and medium-grained and contain megacrysts of biotite. A cleavage is developed in the dykes.

The surrounding rocks

Rocks of the GOC (Thon 1985) form part of the Major Bergen Arc to the east of the Krossnes Granite (Fig. 1). The dismembered character of this complex is evident in the investigated area, and pillow lava, greenstone dykes and gabbro, locally with modal layering, are found within a limited area. Near the granite, primary features of these rocks can only be recognized in tectonic lenses, bounded by ductile shear zones. In a metamorphosed and deformed condition these rocks occur as amphibolites and sheared green schists. To the south, however, the ophiolitic rocks are less deformed, and recent U-Pb ages on zircons from both primary gabbro and an early intrusion (quartz-augen gneiss; Kolderup & Kolderup 1940) have given Arenig ages (R. B. Pedersen pers. com. 1986).

Metasediments uncomformably overlying the rocks of the GOC are preserved in sheared-out synclines in the ophiolitic substrate. The Upper Ordovician to Silurian Ulven Group (Ryan & Skevington 1976) occupies one of these synclines (Fig. 1), and part of it has been correlated with the Holdhus Group in the Samnanger-Os area (Færseth et al. 1977; Ingdahl 1985; Thon 1985). A structural and metamorphic break has been claimed between rocks of the GOC and the younger metasediments (Kvale 1960; Sturt & Thon 1976).

To the NW of the Ulven syncline, two zones of schistose metasediments (the Lysekloster Schists, Fig. 1) are cut by the Krossnes Granite. The rocks in the southern zone have a compositional banding defined by alternations of quartzitic bands and darker, mica-rich, and in places epidote- and chlorite-rich bands. Greenstones, which locally occur together with the metasediments, may have originated as basic lava flows or were tectonically emplaced into the metasediments. The quartzitic bands have thicknesses from a few centimetres to several metres, and have a pinkish colour on weathered surfaces due to a high content of feldspar. The darker, micaceous bands generally have a high content of opaques (predominantly magnetite and pyrite). The metasedimentary sequence must either be considered as a highly-deformed cover sequence to the GOC or as sediments onto which the ophiolite was obducted.

The northern zone is thinner than the southern, and mainly comprises greywackes which are difficult to distinguish from sheared ophiolitic rocks. The similarities may, however, indicate that the greywackes are derived from the ophiolitic rocks. To the east-northeast of Lysekloster, an isoclinically folded marble is associated with greywackes and minor quartzitic schists. The age of the marble is unknown as no fossils have been recovered. The metasediments in the Lysekloster area may be equivalent to similar rocks in the lower parts of the Upper Ordovician to Lower Silurian Holdhus Group or Ulven Group, but the sediments may also be of different ages.

Metasediments with centimetre-thick bands of meta-chert are associated with the ophiolitic rocks in the northwestern part of the Svartevatnet area (Fig. 1). The chert has a pink coloration due to high contents of small spessartine-rich garnets. Similar metasediments are found associated with rocks of the GOC in the nearby Os area (Ingdahl 1985) as well as in the caprock to the Karmøy ophiolite (Solli 1981). The chert-lutites near Svartevatnet appear therefore to be closely related to the rocks of the GOC. The absence of chert-lutite in the other zones of metasediments described above as well as the absence of potassium-feldspar-bearing quartzite in association with metachert indicate that there are at least two and probably three different metasedimentary sequences in the area.

The contact between the GOC and the Anorthosite Complex is marked by a zone of mylonitic rocks which comprise both granitoid gneisses and metasediments (Fig. 1). The latter are both amphibole-garnet-micaschists and protoquartzites, which are very similar to the mylonitized gneisses. The zone can be followed for tens of miles, and bands of non-fossiliferous marble occur among the metasediments to the NE.

Similar rocks are found along the northern side of the Krossnes Granite. Also here a mylonitic foliation is pervasive in the rocks, as is an associated shape fabric/mineral lineation. These rocks are locally difficult to distinguish from the mylonitic Krossnes Granite, and their origin is usually not easy to demonstrate. However, a few zones of marble coexist with what seems to be mylonitized psammites. Green metasediments with epidote nodules not unlike the ophiolite-associated metasediments at Svartevatnet (above), are also present, probably as exotic elements in the zone. Greenschists and gabbroic amphibolites of the GOC also occur, and a kyanite-amphibole-garnet mica-schist is situated structurally beneath the other metasediments, separated from the Anorthosite Complex by a mylonitic to ultramylonitic gneiss. Kyanite occurs as porphyroblasts which have suffered little deformation compared to the finite strain in these rocks. The kyanite is stable in equilibrium with biotite, quartz and albite.

Between Svartevatnet and Jordevatnet the intrusive relationships are strongly obscured by both post-intrusion ductile strains and cataclastic zones up to tens of metres in thickness. The presence of mylonitic gneiss and metasediments similar to those to the west has, however, been noted.

In the northern parts of the granite, an increase in ductile deformation in the granite towards the northern margin can be observed. There is a transition from nearly undeformed granite (Fig. 2a), through foliated granite (Fig. 2b) to mylonitic granite near the contact. Typical S-C mylonites (e.g. Lister & Snoke 1984) are developed in the deformed granite (Fig. 2b), and the relation between the S- and C-surfaces indicates overthrusting to the NW. Xenoliths are thin, dark bands in the mylonitic granite. Isoclinically folded and rodded veins of quartz are also present. The contact between the mylonitic granite and the gneissic metasediments is not easily defined, and the contact (Fig. 1) has been drawn between deformed granite with large xenoliths of country-rocks, and metasediments, gneisses, greenstones and gabbros with dykes of granite.

At Hamresåta (Fig. 1) the Krossnes Granite is not so deformed. Cross-cutting granitic dykes and foliated xenoliths in the granite indicate considerable pre-intrusion strains. Minor bodies of granite in the mylonite zone to the north of the Krossnes Granite may also be little deformed. In addition, they enclose xenoliths containing an older, mylonitic foliation. These small granitic bodies may possibly represent somewhat later intrusions than the main pluton.

Structures

The Krossnes Granite cuts an older mylonitic foliation, but is itself strongly deformed towards its northern and northeastern margin (Fig. 1). However, cross-cutting relationships are locally preserved also to the north, probably due to inhomogeneous strains.

Some deformation is also evident within the least deformed parts of the Krossnes Granite, but the much lower strains here are taken up along discrete shear zones which often follow large, tabular xenoliths. Where xenoliths have been netveined by the granite and later deformed, tectonic conglomerates may occur.

The main, often mylonitic Scandian foliation of the rocks of the Major Bergen Arc has a NE-SW trend, generally with steep to moderate dips to the SE. This trend continues into the Krossnes Granite (Fig. 1). The shape fabric, rodding and mineral lineation associated with this foliation is sub-horizontal or dips to the SE, having the same trend inside and outside the granite. In deformed conglomerates in the Ulven area, the lineation is seen to be a stretching lineation. Tight to isoclinal folds have fold-axes sub-parallel with the lineation. Their axial surfaces are rotated by later folding, and is gently to moderately dipping to the SSE in the northern areas, and vertical or steep to the SE in the southern areas. This is the same fabric orientation as seen elsewhere in the southern part of the Major Bergen Arc (Ingdahl 1985).

Open to tight, asymmetrical folds with a north-westerly vergence (F3 in Fig. 5) affect both the mylonite foliation within the mapped area and the granitic dykes. These folds have been recognized many places in the Bergen Arc System and represent a major late phase of Scandian folding (e.g. Henriksen 1979; Ingdahl 1985; Fossen 1986). The folds are best developed in the southern and eastern parts of the mapped area, while they are only occasionally observed to the north.

Late faults or fracture systems are common (Fig. 1) and are marked by cataclasites. Common directions of the fault zones are NE-SW, NW-SE and N-S. They are related to a major fault system along Raunefjorden-Hjeltfjorden which continues to the south (probably of latest Palaeozoic or later age, e.g. Naterstad in Gabrielsen & Koestler 1985). This fault system cuts the NE-SW system near Drange (Fig. 1). The NE-faults dip about 50–70 degrees to the northwest, while the N-S system is sub-vertical.

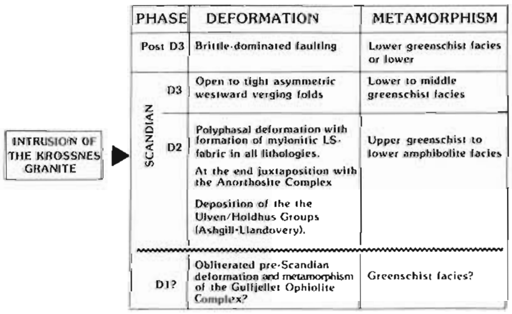


Fig. 5. Flow diagram which shows the intrusion of the Krossnes Granite in relation to the regional geology.

Pseudotachylyte is represented in these mylonites.

The mylonites are intruded by granitoid bodies and dykes which themselves are variably deformed. The granitoids were probably emplaced as sills along the mylonitic foliation, thus giving rise to the elongated form of the intrusions (Fig. 1). Clear cross-cutting relationships with a mylonitic foliation are occasionally present, although post-intrusion strains commonly overprint the intrusive relationships.

Metamorphism

Almandine-rich garnets occur in the metasediments adjacent to the granite, indicating upper greenschist facies or lower amphibolite facies metamorphism. The presence of chlorite together with hornblende porphyroblasts suggests uppermost greenschist facies close to lower amphibolite facies metamorphism (Miyashiro 1973; Winkler 1979). The presence of kyanite along the contact with the Anorthosite Complex may indicate somewhat higher pressures in this part of the area. The amphiboles, garnets and kyanites occur both as porphyroclasts and porphyroblasts, and are interpreted as having grown during the main, late Caledonian deformation (syn to post D2 in Fig. 5). Uppermost greenschist to lowermost amphibolite facies conditions during this deformation are also indicated by microchemical mineral analysis from both the major and minor Bergen Arc (Fossen 1986 and in prep.).

Contact relationships between the Krossnes Granite and the surrounding rocks

Intrusive contacts are well preserved within the area near Danielsviken (Fig. 1). Here the Krossnes Granite is nearly undeformed. Along the margins, the granite sends apophyses into the country rock and cuts an older, strong foliation (Fig. 4). The granite dykes have been buckled and tightly folded, but still preserve crosscutting relationships. Boudinage of narrow dykes reflect the post-intrusion flattening strains. Post-intrusion deformation has not resulted in any strong fabric in the granite in this part of the area. Cross-cutting granite dykes also occur on small islets to the SE, and are restricted to a relatively narrow zone around the Krossnes Granite. The granite thus post-dates the mylonitic foliation in the rocks of the Major Bergen Arc, and is itself affected by relatively moderate post-intrusion strains in this area.

Fig. 4. Dykes of the Krossnes Granite in strongly foliated metasediments near Danielsviken. (UTM 297-6678).

From Danielsviken (Fig. 1) to the NE, the contact is modified by late faults, marked by cataclastic zones. Apart from these, the massive, coarse-grained granite is virtually undeformed.

At Sperreviken (Fig. 1) the contact has been affected by ductile deformation and the granite is in tectonic contact with mylonitic greenstones. The effects of shearing rapidly decrease into the granite.

Northwards from Sperreviken, the primary intrusive nature of the contact is obscured by ductile strains. In the Lysehornet-Svartevatnet area there are mylonitic rocks of uncertain origin. Some have the appearance of mylonitic quartzites, and they occur within little-deformed granitic rocks of the Krossnes Granite. At the southern end of Svartevatnet, granitic dykes cross-cut mylonite-gneiss.

Displacement of the Anorthosite Complex by faulting is evident to the SW of Kalandsvatnet (Fig. 1). The fault zone is probably dip-slip dominated, as the displacement is evident on the map only where the rocks are not sub-vertical. A fold structure in this area is probably formed by rotation of the rocks during faulting. Rigidity of the granite body during deformation seems to be responsible for the strain released along its margins.

Discussion and conclusions

The Krossnes Granite and the adjacent sediments have been interpreted as a separate nappe, the 'Fanafjell Nappe' (Sturt & Thon 1978), representing the uppermost tectonic unit in the Bergen nappe sequence. Sturt & Thon (1978) claimed that 'the Fanafjell Nappe transgressed the already folded thrust plane between the Anorthosite Complex and the Major Bergen Arc'.

This work has shown that the Krossnes Granite preserves intrusive contacts with Ordovician and other rocks of the Major Bergen Arc to the SE, partly also to the north and east. The granite crosscuts a strong planar fabric which also seems to affect rocks of the Ulven and Holdhus Groups (Ashgill-Llandovery age) in the Os area of the Major Bergen Arc. However, the Krossnes Granite is strongly affected by late Caledonian deformation in its northern and north-eastern parts, and the strong LS-fabric in the rocks of the Major Bergen Arc can be continuously traced into the granite. This suggests that the intrusion of the Krossnes Granite was syn-tectonic with respect to the main (Scandian) phase of Caledonian deformation (D2), and that the granite was post-dated by the major refolding of the area (D3). The preliminary Rb/Sr age of 440 ± 50 Ma for the granite is not in conflict with a Scandian age. The Krossnes Granite therefore intruded the Gulfjellet Ophiolite Complex and metasediments of the Major Bergen Arc at an early stage of the final 'mis-en-place' of the Bergen Nappe System. The relationship of the granite intrusion to the regional geology is shown in Fig. 5.

An increase in strain towards the north, i.e. towards the contact with the Anorthosite Complex is unequivocal both in rocks of the GOC and the Krossnes Granite. The northern contact represents a major zone of shear which was active during the Scandian movements in the Bergen Arc System. The presence of kyanite along this shear zone indicates relatively high pressures during the development of the low-grade assemblage. High-pressure conditions are reported from Caledonian shear zones in anorthositic rocks in the Anorthosite Complex (Austrheim & Griffin 1985). Late Caledonian ages from these mineral paragenesis are indicated. Hence, it seems natural to link the high-pressure shearing in the Anorthosite Complex to the medium- to high-pressure shearing along the contact between the Krossnes Granite and the Major Bergen Arc.

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