A GEOLOGICAL TRAVERSE ACROSS THE PYROXENE-GRANULITES OF JOTUNHEIMEN IN THE NORWEGIAN CALEDONIDES

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Rocks of the Jotun stem between Tyin and Böverdalen fall into two groups: (a) peripheral gabbros, and granitic rocks of amphibolite facies metamorphism, sometimes retaining igneous textures and (b) a core of ultramafic rocks and pyroxene-gneisses of pyroxene-granulite metamorphism. The core is coextensive with the deep, dense root of the Caledonides on the geophysical model, the peripheral group with a widely-extending shallower sheet. The structure of the two groups is described. In the light of recent work on the surrounding Eocambrian, it is proposed that the peripheral group was in part emplaced magmatically at high level, eroded and unconformably covered by Eocambrian sparagmite, whilst the core rocks were metamorphosed at pressures > 4kb and tectonically elevated from a root in the Faltungsgraben during the Caledonian orogeny.

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The principal outcrop of rocks of the Jotun stem of Goldschmidt (1916) forms a north-easterly extending belt 170 km long, and between 50 and 80 km wide, near the south-eastern border of the Norwegian Caledonides (Fig. 1). The north-western margin of the Jotun tract is fairly straight, but the south-eastern border is sinuous, with extensive lobes and outliers.

The rocks included in the Jotun stem are ultrabasic to acid gneisses of the pyroxene-granulite facies of metamorphism, anorthosites, and various gabbroic and granitic bodies of more obviously intrusive aspect.

The Jotun stem rocks, as a whole, show overthrust relationships to the surrounding metasediments, with extensive mylonitic border zones. They have long been regarded as a far-travelled sheet, overthrust south-eastwards from an unexposed root zone to the north-west (Holtedahl 1960, p. 188). Gravity surveys (Smithson 1964, Smithson & Ramberg 1970) have more recently shown, however, that the dense Jotun rocks probably extend to a depth of 6 to 13 km below the axial region of the main outcrop.

Though there is a considerable amount of data available on the geological structure around the borders of the area of Jotun rocks, little geological work has been done in the interior of this tract. The present contribution presents information on a transect across the main outcrop, from the lake Tyin in the south to upper Böverdalen and Leirdalen in the north (Figs. 1

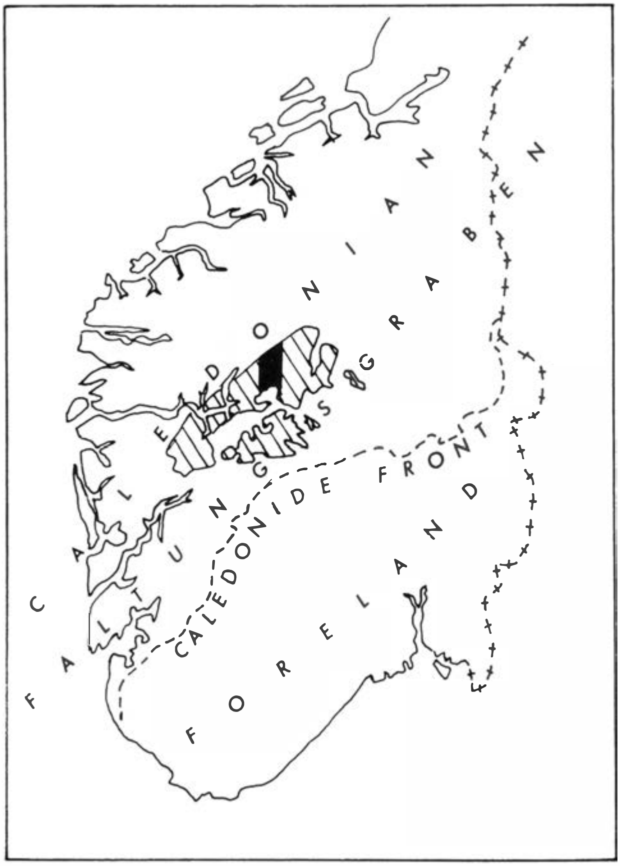

Fig. 1. Southern Norway, showing the main outcrop of Jotun stem rocks (diagonal lines) and the area mapped (black).

and 2). It is intended as a preliminary to an account of the petrology of the pyroxene-granulite facies rocks.

Structural elements

For descriptive purposes the area may be divided into two parts, the region north of the Tyin-Gjende Fault (Fig. 3), largely made of pyroxene-granulite facies rocks, and that to the south, where the rocks belong to the epidote-amphibolite facies. The structural elements will be described in the following order:

Faults of the northern (pyroxene-gneiss) area.
Thrust sheets south of the Tyin-Gjende Fault.
Layered structures north of the Tyin-Gjende Fault.

FAULTS OF THE NORTHERN (PYROXENE-GNEISS) AREA

The faults of the northern area are shown in Fig. 3. The principal faults and some of the subsidiary faults have been located, in part at least, on the

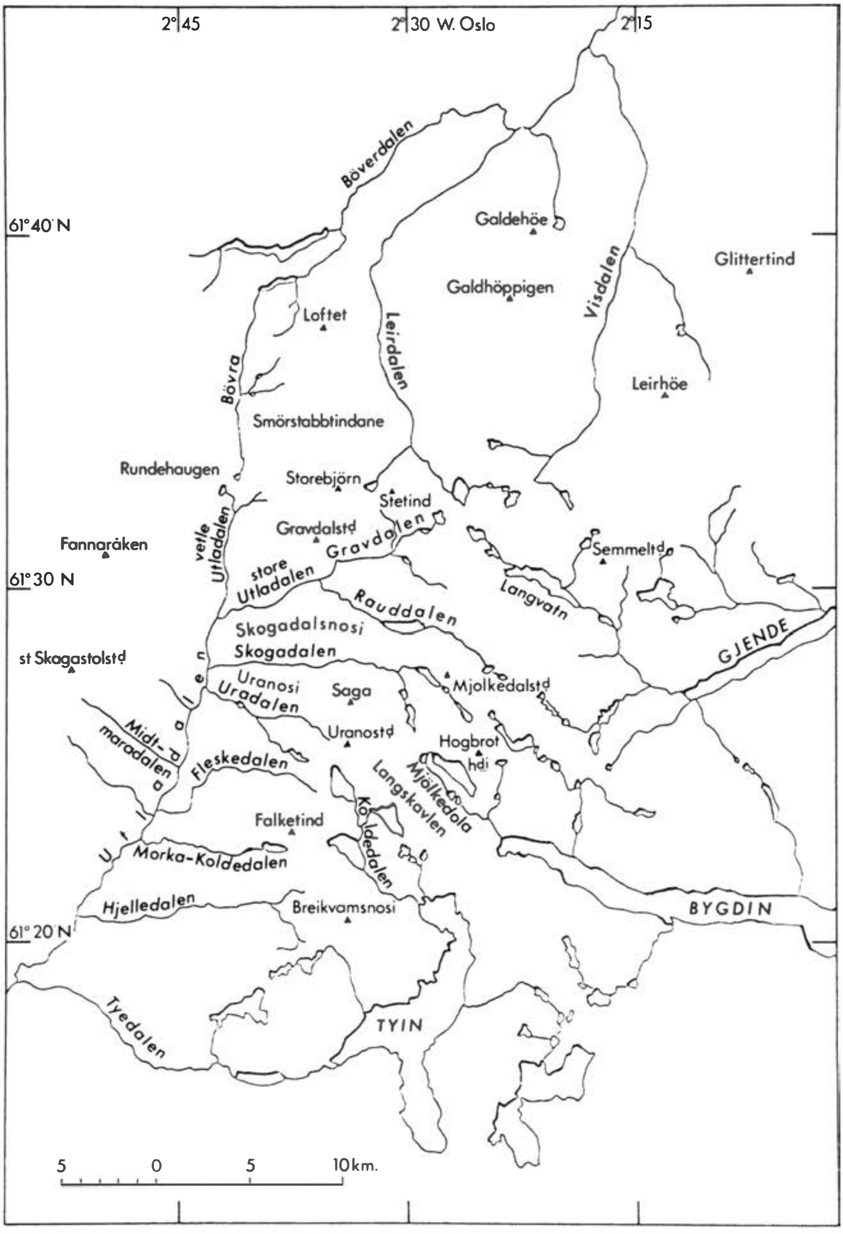

Fig. 2. General topography of the area studied.

ground. Many of the subsidiary faults, however, have been plotted from features visible on air photos.

Tyin-Gjende Fault

This fault extends from Breikvamsnosi, N. of the lake Tyin, east-northeastwards to the western end of the lake Gjende (Battey 1965). (Fig. 2

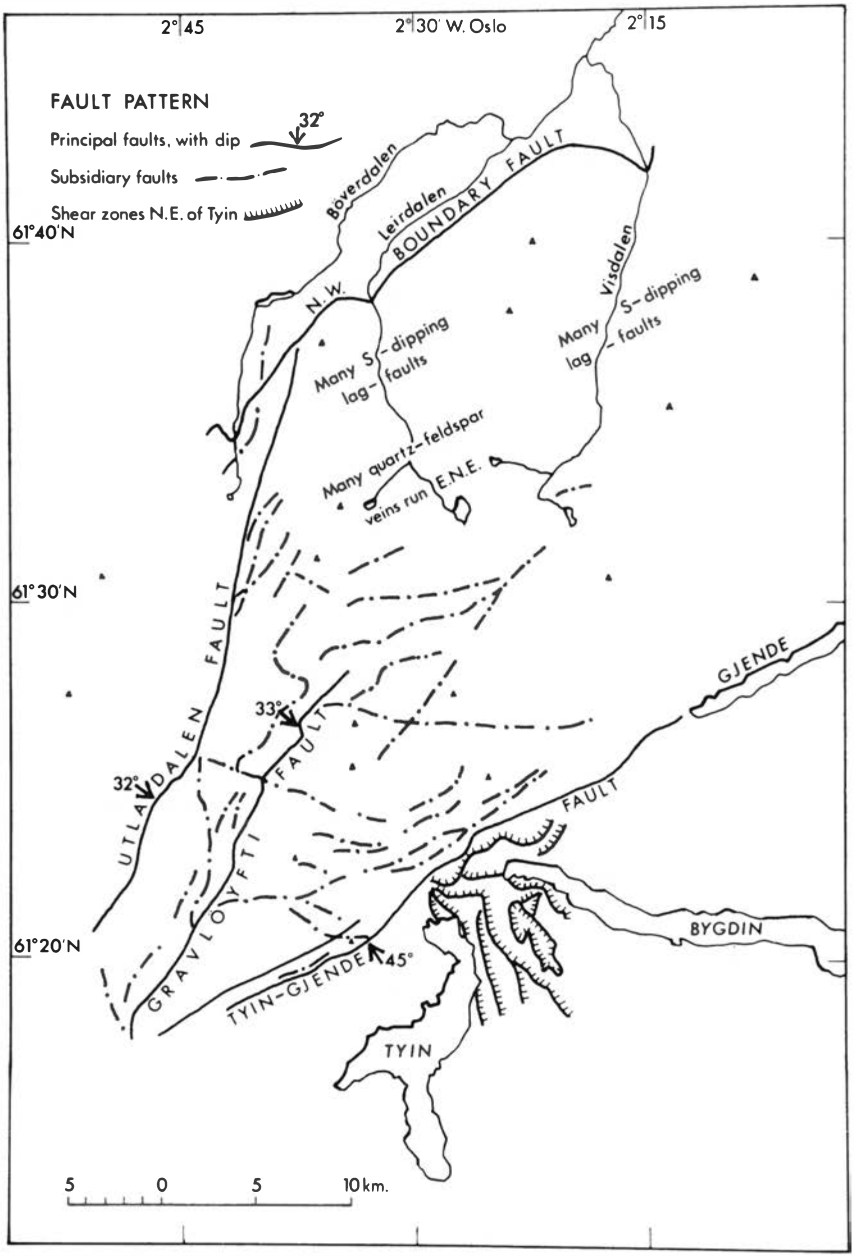

Fig. 3. The fault pattern.

shows most of the place-names used in the text.) Its line is clearly marked by a topographic feature along most of its length, and the trend of the outcrop across the valley Mjölkedola (Fig. 3), as well as featuring on the east face of Breikvamsnosi (Fig. 4), suggest a dip of about 45° to 50° to the NNW. Where the fault crosses the Mjölkedola, its plane dips NNW at 40°, and mylonite layers here, and to the south-west, dip N or NW at angles of

Fig. 4. Breikvamsnosi, looking eastwards, showing the featuring produced by the northward dip of the Tyin-Gjende Fault and associated shear-planes. The lower ground to the left is underlain by arkose (sparagmite).

20° to 50°. North of Geithö, halfway between Mjölkedola and Gjende, mylonites dip 30° to 40° to NW.

On the air photos this fault appears to continue west-south-westwards from Breikvamsnosi for a further 8 km; but this extension has not been followed on the ground.

Over the length from Mjölkedola to Gjende, the Tyin-Gjende Fault separates gabbro with relict igneous texture to the south, from a belt, up to 1 ½ km wide, of variable rocks, collectively called feldspathic crush-rock, to the north (Fig. 5). These crush-rocks are pink-coloured, quartzo-feldspathic types, with epidote and chlorite as dark minerals, and they enclose and form veinlets in fragments of pyroxene-gneiss and gabbro. They have crystallized under epidote-amphibolite facies conditions, and represent an episode of retrograde metamorphism, and possibly of acid intrusion, later than the rocks on either side of them. The feldspathic crush-rock is followed northward by a large area of pyroxene-granulite facies rocks.

It is noteworthy that the line of the Tyin-Gjende Fault is closely followed by the −50 mgal contour on the Bouguer anomaly map (Smithson 1964) and lies at the lip where the lower surface of the Jotun rocks plunges down towards its deep root on the geophysical model. This suggests that the Tyin-Gjende Fault may be a feature of major importance in defining the form of the hidden part of the pyroxene-gneiss massif.

Utladalen Fault

This fault extends from the western edge of the glacier Smörstabbreen, east of the upper part of the river Bövra, on a bearing of about 200° along the

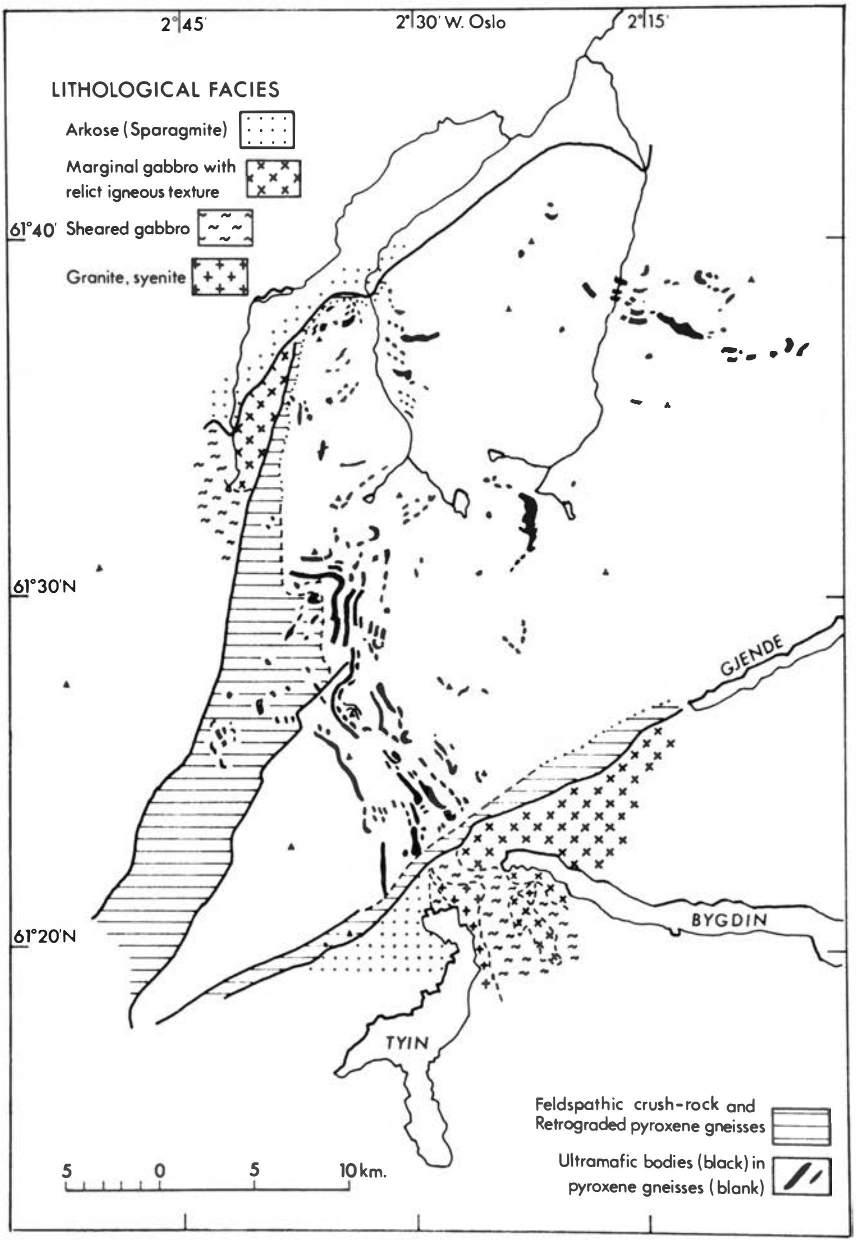

Fig. 5. Distribution of lithological facies.

eastern side of vetle Utladalen, and then along Utladalen at least as far as Hjelledalen. In the north it separates an area of gabbroic rocks in the upper reaches of the Bövra, that in part retain their original igneous texture, from pyroxene-gneisses that build Loftet and Smörstabbtindane (Fig. 5). Along its course is a zone of intense disturbance, accompanied by the emplacement of pink, feldspathic fault-rock, with feldspar porphyroblasts sometimes producing augen-structure. It thus shows marked similarities, overall, to the Tyin-Gjende Fault in the south. The gabbros with relict igneous texture east of the Bövra, between the river and the Utladalen Fault, pass, west of the Bövra, into a tract of highly-sheared, often amphibolised gabbro-type rocks on Rundhaugen. These sheared rocks show analogies with the highly-sheared epidote-amphibolite facies rocks south of the Tyin-Gjende Fault. This emphasises the symmetrical arrangement of zones either side of the pyroxene-gneiss core.

Followed south into vetle Utladalen, the disturbance caused by the fault continues, with augen-gneiss on Fugleberg and conspicuous masses of feldspathic rock along the Utla.

From here to the junction of vetle Utladalen and store Utladalen the fault has not been followed on the ground, but the air photos show it clearly marked by an erosional trench across the south-west spur of Hillerhö, just north of store Utladalen. From this point it has been traced on the ground, as a zone of intensely-sheared amphibolic rocks with slickensides and great contortion, through the western tip of Skogadalsnosi to Uradalen. Thence its trace on the air photos continues on a bearing of 200°, to cross the Utla 1 km above the Midtmaradalen confluence. It crosses back again 1 km above Vetti. The dip, calculated from the swing of its outcrop between these two crossings of the Utla, is 32° to ESE. Along the section from store Utladalen to Uradalen, the pink feldspathic rock seen in the upper reaches of the Bövra is not prominent. Little is known of the rocks west of the Utla, but examination of Goldschmidt's thin sections of rocks from Hurrungane suggests that, in the middle reaches of the Utla, the pyroxene-gneisses on either side of the fault are essentially similar. The gravity data available at present do not suffice to show whether any important change in the Bouguer anomaly takes place along the line of the fault.

Gravlöyfti Fault

East of the Utladalen Fault lies a zone about 4 km broad, in which the effects of shearing and disruption of the layered ultramafics and pyroxene-gneisses are very marked (Fig. 5). This zone may be said to be bounded on the east by the Gravlöyfti Fault, which has been mapped across Uradalen and Uranosi by R. C. Swainbank, and traced south-south-westwards as far as the edge of Tyedalen on the air photos. It runs parallel to the Utladalen Fault, and its dip, calculated from the swing in outcrop across Uranosi, is 33° to ESE. Between the Gravlöyfti Fault and the Utladalen Fault, the NNW-trending layered structure of the pyroxene-gneiss to the east is shredded up into short sections and isolated fragments retaining the NNW trend, separated by shear planes and faults striking in general NNE and dipping ESE.

This zone of disturbance between the Gravlöyfti and Utladalen Faults disappears under Smörstabbreen. East of the point where it disappears, there is a pronounced change in strike of the layered gneisses, on Gravdalstind, but at present the relation between this swing in strike and the fault zone is not known, because the fault zone is masked by the glacier.

North-west Boundary Fault

This fault, which runs along the escarpment on the south side of lower Leirdalen and Böverdalen, intersects the northern end of the Utladalen Fault west of Loftet. To the west of this intersection, the maps of Landmark and Rekstad (Landmark 1949) give rather different interpretations of its course, but it passes north of Rundehaugen. North-eastwards of Loftet its outcrop runs on a bearing of about 55°, crossing the river Leira and continuing along the south-east side of the lower part of Leirdalen into the area where it has been mapped by Strand (1964).

North-eastwards from here, Strand identifies a sheet of crystalline rocks (plagioclase-rich gneiss, saussuritised gabbros or diorites, and striped and banded gneiss), with 'Valdres Sparagmite' lying upon them, which is thrust over Eocambrian and Lower Palaeozoic sediments. This sheet constitutes Strand's Otta Nappe (or Lower Jotun Nappe) which is in turn overthrust by the Upper Jotun Nappe.

West-south-west of Loftet, there are laterally tapering sheets of light-coloured, closely-striped sandstone (sparagmite), intercalated with highly-sheared, amphibolised or chloritised gabbroic rocks. The sheets of the two rock-types are elongated NNE and dip ESE at angles of 20° to 30°. This is interpreted as a zone of imbrication, which has been followed for 4 km in this area.

On the slopes rising to the north foot of Loftet, light-coloured sandstones extend to a height of about 1350 m. Above this, sheared, amphibolised gabbros enter and continue to a height of 1631 m. These are succeeded up the north spur of Loftet by pyroxene-gneisses with interlayered sheets of peridotite and pyroxenite. In the pyroxene-gneisses, the foliation and the ultramafic sheets alike dip steeply northwards; but the rocks are cut by shear-planes dipping SE, which produce retrograde metamorphic effects converting the pyroxene-gneisses to amphibolic rocks.

The North-west Boundary Fault of the Jotun massif has long been regarded as a thrust, but the direction and scale of movement on it has been uncertain. Goldschmidt's view that the Jotun rocks were rooted in the Caledonian Faltungsgraben (Fig. 1) implies outward, north-westwardly directed thrusting. Holtedahl's opinion, first expressed in 1936 (see Holtedahl 1960, p. 188), that these rocks everywhere rest upon a thrust-plane and, having no roots in their present area of outcrop, represent a far-travelled mass from the north-west, would require south-eastward movement on the North-west Boundary Thrust. There is now some additional evidence on this question.

Cowan's (1966) description of a synclinorium of Lower Palaeozoic rocks in Böverdalen, strongly overturned to the north-west, suggests tectonic transport in that direction. McAuslan (1967), in a study of the Lom district, suggests that the Ottadalen Nappe, formed in the first phase of Caledonian movement, may be a large fold overturned to the north, with its uninverted limb resting upon the Basal Gneiss, though he does not regard the evidence for this fold as conclusive. If his interpretation is correct, this fold would also indicate a northward direction of movement. In the third phase of movement recognised by McAuslan, major folding took place that led to a general southerly dip of the tectonic units in the area. From the Sjodalen area, also studied by McAuslan, no definite indications of the direction of tectonic transport are reported.

The gravity survey by Smithson (Smithson 1964, Smithson & Ramberg 1970), with its clear indication of from 6 to 13 km thickness of gabbroic rocks below the long axis of the massif, gives strong support to Goldschmidt's conclusion that the Jotun massif is rooted in the Faltungsgraben.

Taken as a whole, the evidence now available favours an hypothesis of outward thrusting of the Jotun rocks to north-west and south-east, away from the axial region of the Faltungsgraben.

Lags above the North-west Boundary Fault

In a belt some 9 to 10 km wide south-east of the North-west Boundary Fault the pyroxene-gneisses and ultramafics are cut by numerous shear-planes dipping south-eastwards at angles of about 25°. The scale of movement on these surfaces is variable, from a few centimetres to tens of metres; it is accompanied by bending of the foliation planes in the gneisses and retrograde metamorphism of the pyroxene to amphibole (Fig. 6), and the

Fig. 6. A lag-fault cutting pyroxene-gneiss, east wall of Visdalen near Spiterstulen. The gneissic foliation is bent so as to indicate the sense of movement and the gneiss is darkened by amphibolisation as the bending commences. The fault plane is occupied by a typical pegmatitic vein.

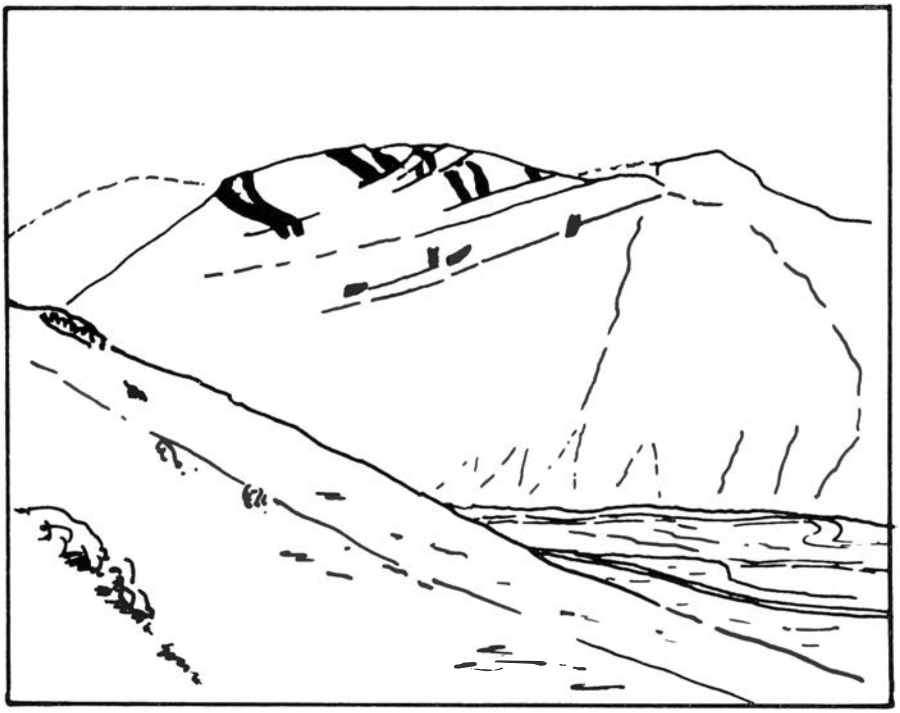

Fig. 7. View westward across Leirdalen to Loftet. Lag faults dipping southward (to the left) disrupt north-dipping peridotite layers shown in black.

shear-planes are often occupied by a pegmatite of quartz and feldspar a few centimetres in thickness. The sense of movement on these shear-planes is in most cases such that the rocks above the plane have slipped down the dip of the plane: that is, they are low-angle normal faults, or lags, not thrusts.

The lags are well seen from the eastern side of Leirdalen, near the line of the North-west Boundary Fault, looking across to the north spur of Loftet on the opposite side of the valley (Fig. 7). In this view, numerous separate bodies of ultramafic rock can be seen dipping north in the flank of Loftet. They are broken by slide-planes dipping southwards, up Leirdalen, and strips of ultramafic rock have been drawn into the planes of movement. The ruptured ends of the north-dipping ultramafic layers have, in some cases, been dragged into the slides in such a way as to indicate the down-dip (southward) sense of movement of the rocks above the movement-plane.

The most striking example of this effect, is on Rauhamrein, on the eastern side of Leirdalen. Here, a relatively large ultramafic body, dipping generally northwards, is dragged over so as to lie with southerly dip as a partial veneer on the south slope of the hill, descending towards the stream nedre Illåa, where its counterpart crops out on the left bank.

The same sense of movement is shown in lower Visdalen (Battey 1960, p. 199 and Fig. 1). A large number of slides of the same kind, each with only small movement, is exposed in the wall of the cirque on Galdehöe. The aggregate amount of movement represented in this cirque must be tens of metres at least, and may be much more.

Since this lag movement is shown over a fairly wide area, from Loftet to east of Visdalen, and affects the rocks for as much as 10 km south of the Boundary Fault, the total movement involved must be considerable. It is to be noted that the direction of movement, to the south or south-east, is the opposite of that deduced for the Boundary Fault. This may be used as an argument in favour of the movement on the Boundary Fault also being a translation of the upper rocks towards the south-east, as in Holtedahl's hypothesis mentioned above. On the other hand, it may indicate either a mechanism of upthrusting whereby the marginal rocks moved upwards and outwards more readily than the central area, or response to a later phase of central subsidence. In any case, the amphibolisation along the slides shows that they developed under amphibolite facies conditions, presumably during or after uprise of the massif from the depths where pyroxenes are the stable phases.

Late vertical faults

In the cirque on Galdehöe the slide-planes are cut by a north-easterly vertical fault along which is a zone of bright green epidotic rock, with large red feldspar porphyroblasts, representing a later episode of movement, of the same mineral facies as, and perhaps coeval with the principal faults already described. Some of the subsidiary faults on Fig. 3 probably belong to this group.

THRUST SHEETS SOUTH OF THE TYIN-GJENDE FAULT

The hills east of Tyin are underlain by rocks for the most part metamorphosed in the epidote-amphibolite and upper greenschist facies, and there is no evidence to show that they have ever undergone a period of granulite facies metamorphism (McRitchie 1965).

McRitchie reports that the rocks of this area occur as a pile of sheets separated by near-parallel shear-planes. The original attitude of the shear-planes, though masked by subsequent refolding, is thought to have been flat-lying.

The following sheets are recognised (Fig. 8):

Mjölkedola Purple Gabbro (Marginal gabbro with relict igneous texture)
Vennistordalen Syenite
Mosaryggin Sheared Gabbro
Tvindehaugen Granite
Highly-sheared amphibole gneisses
Sparagmite

Chiefly within the Mosaryggin Sheared Gabbro, but also in the highly-

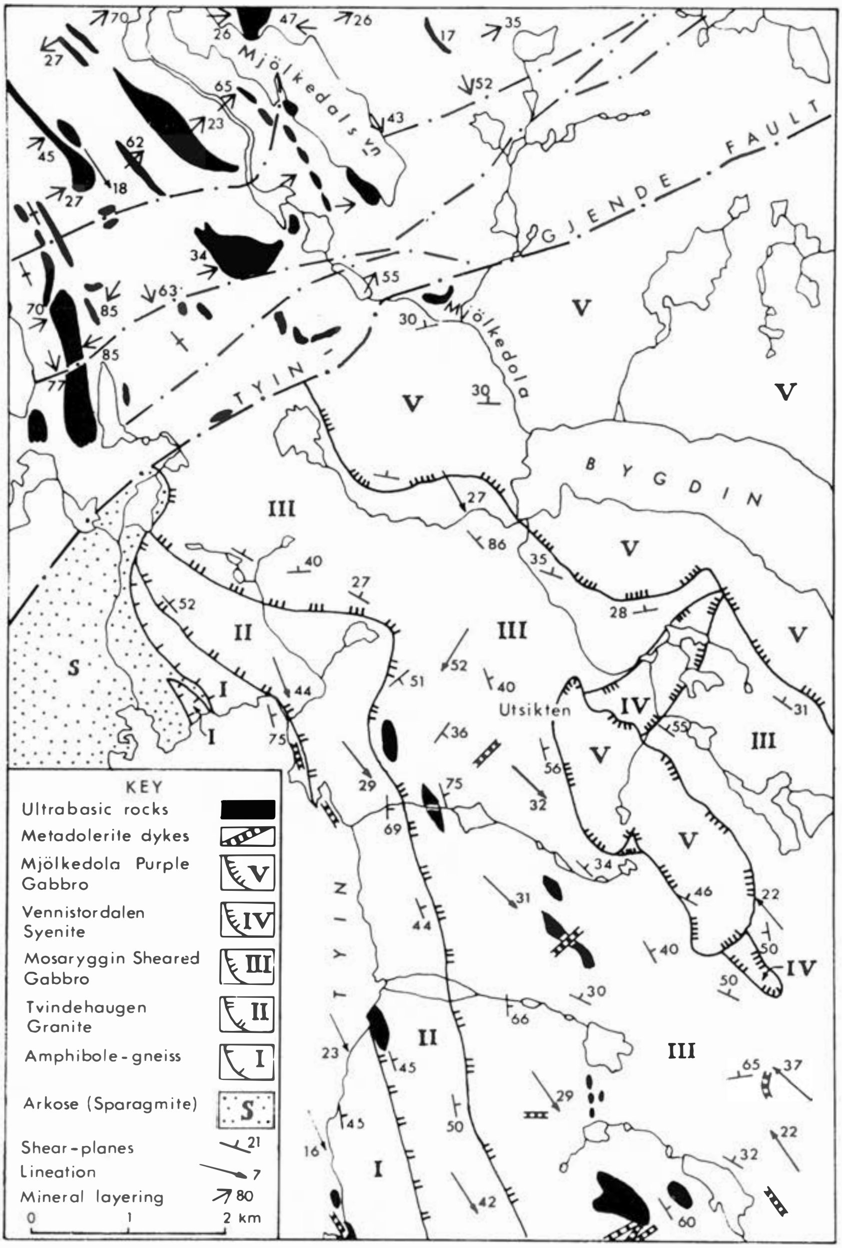

Fig. 8. Thrust-sheets and intrusions south of the Tyin-Gjende Fault between the lakes Tyin and Bygdin.

sheared amphibolic rocks below the Tvindehaugen Granite, are lenses of ultramafic rocks up to 30 m wide and three or four times this in length. These ultramafics differ from the bodies north of the Tyin-Gjende Fault in containing substantial amounts (up to 28 vol. percent) of plagioclase. They are contained in shear-zones cutting the host rocks, aligned in a north-north-westerly direction parallel to the foliation. It may be noted that the belt in which these ultramafics occur is aligned rather closely with the concentration of ultramafic layers on the west side of Langskavlen, north of the Tyin-Gjende Fault; but the significance, if any, of this fact is not clear. Metadolerite dykes are also recognised (Fig. 8) which cut and are chilled against, altered gabbros of the thrust sheets. The dykes are cut off by the thrusts.

After development of the shear-planes, under epidote-amphibolite conditions, the resulting foliation was deformed by folds with north-westwardly directed axes, long, gently-dipping north-east limbs and short, steep or overturned south-west limbs. The fold-axes coincide in direction with those north of the Tyin-Gjende Fault, and stereograms of poles to the foliation north and south of the fault are almost identical (Figs. 9 and 10). The axes of minor folds follow the same direction.

A later folding on north-easterly axes has produced south-east-facing monoclines south of the Fault, and results in a split in the girdle of poles to foliation in Fig. 10. Warping with this axial trend is reported from the east face of Utsikten and north of the lake Dryllin (both localities north-east of Tyin).

Lineations south of the Tyin-Gjende Fault trend north-westwards and, again, coincide in direction with those to the north of the Fault (Fig. 11).

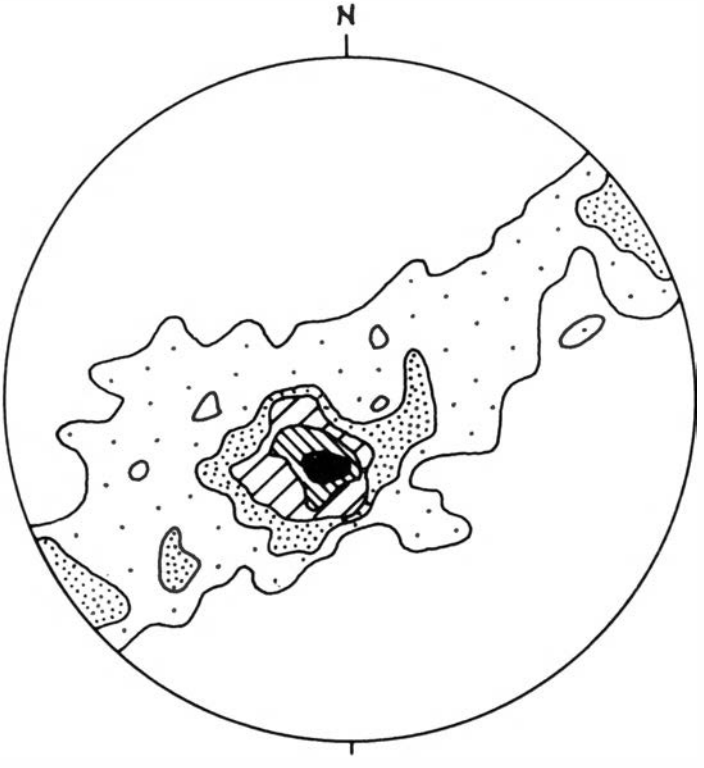

Fig. 9. Stereogram (lower hemisphere) of poles to foliation in the area between the Tyin-Gjende Fault and Rauddalen. Contours at 1, 3, 6, 10 and 15% per 1% area.

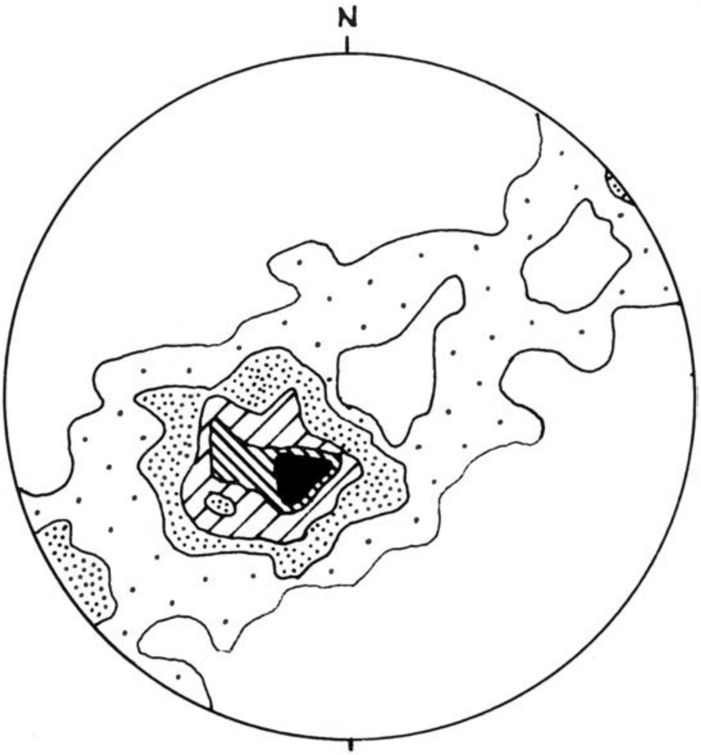

Fig. 10. Stereogram (lower hemisphere) of poles to foliation south of the Tyin-Gjende Fault and east of the lake Tyin. Contours at 2, 4, 6, 10 and 16% per 1% area.

We have, therefore, a remarkable coincidence of fold axial direction and of lineation direction in rocks of very different metamorphic grade, north and south of the Tyin-Gjende Fault.

The Mjölkedola Purple Gabbro, interposed between the Fault and the sheared rocks farther south, shows the following structural elements:

Textural and mineralogical foliation and layering of varying distinctness that stands vertical and strikes north-north-west. The foliation becomes more marked and becomes bent near the flat-lying movement planes noted in the third paragraph below. The rock is, however, markedly less foliated than the gneisses to the north of the Fault.

Quartz-muscovite-feldspar veins, vertical and striking east-north-east, which cut the foliation. These may be compared with the pegmatitic veins striking east-north-east in Gravdalen and Leirdalen in the region north of the Fault. Note that, as illustrated in Fig. 12, they cut the bent foliation that in turn seems to owe its curvature to the flat-lying movement planes (see below).

Pegmatites striking east-north-east and dipping gently north-north-west, which form good topographic features either side of the stream Mjölke-

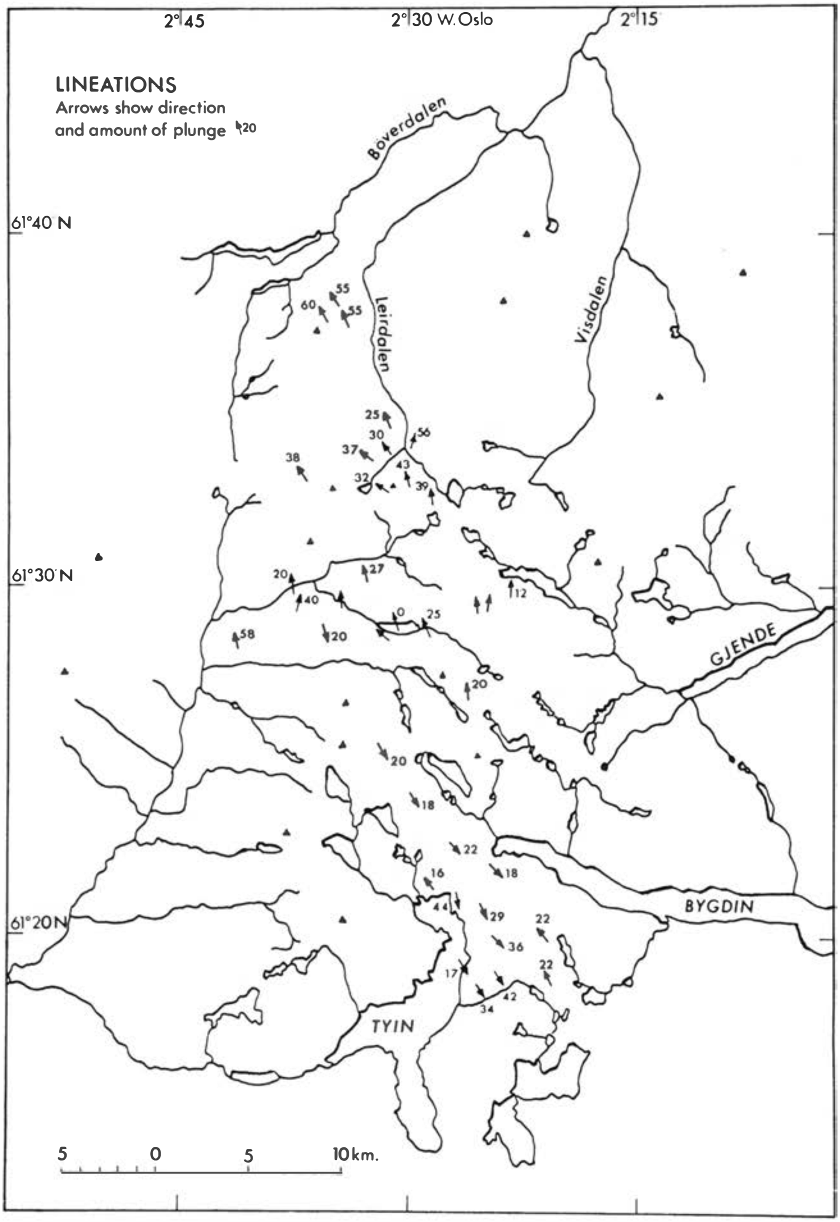

Fig. 11. Lineations in the area studied.

dola. They appear to cut the vertical pegmatites (Fig. 12) and have associated with them a marginal bleached and amphibolised zone of altered gabbro. As the vertical pegmatites cut curved foliation near the flat-lying pegmatites the two cannot be very different in age. Recumbent folds overturned to the south-east in the flat-lying pegmatites indicate that they were emplaced syntectonically, and corrugations on their upper surfaces constitute a north-westerly lineation. A pegmatite of this group has been dis-

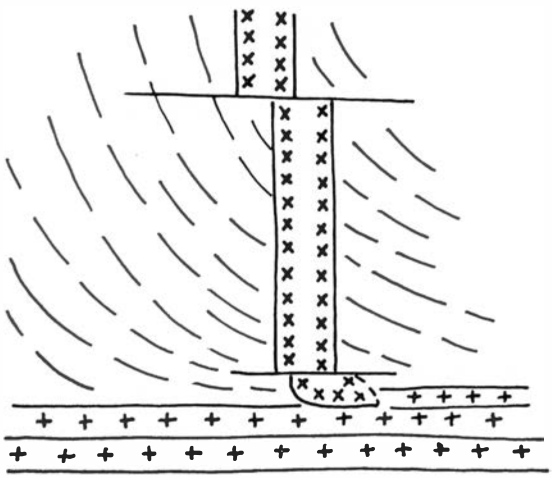

Fig. 12. Vertical east-trending pegmatite vein in Mjölkedola stream valley cuts curved foliation in Purple Gabbro, and is cut by flat-lying shear-planes, the lowest of which is occupied by a later pegmatite sheet.

placed a few metres by a small branch of the Tyin-Gjende Fault, while the gabbro as a whole is cut off by the Fault.

These flat-lying pegmatites may perhaps correlate with the lags, illustrated in Fig. 6, in the pyroxene gneisses.

The lower surface of the Mjölkedola Purple Gabbro is marked by a zone of platy phyllonitic gabbro and associated quartzo-feldspathic pegmatite some 10 to 15 m thick in places. Tight fold-noses overturned to the south-east, in the phyllonites, have axial planes dipping northwards, parallel with the shear foliation.

The style of deformation in the Mjölkedola Purple Gabbro has features in common with that of the tracts to north and south; but the rock differs from the pyroxene-gneisses to the north by retaining igneous texture in places and being in general less strongly gneissic, whilst it has a gabbroic mineralogy of higher temperature facies than the rocks to the south. Finally, from the gravity data (Smithson & Ramberg 1970), it appears that the rocks assigned to the Jotun group, south of the Tyin-Gjende Fault, are perhaps one quarter or one fifth the thickness of those farther north and constitute part of the 2 to 4 km thick plate of rocks extending south from the thick axial zone of the Jotun massif.

LAYERED STRUCTURES NORTH OF THE TYIN-GJENDE FAULT

Mineralogical layering is widespread in the pyroxene-granulite facies rocks north of the Tyin-Gjende Fault (Fig. 13), but is not developed everywhere to a uniform degree. Where well-developed, it pervades the feldspathic pyroxene-gneisses and ultramafics alike, and consists of the concentration of

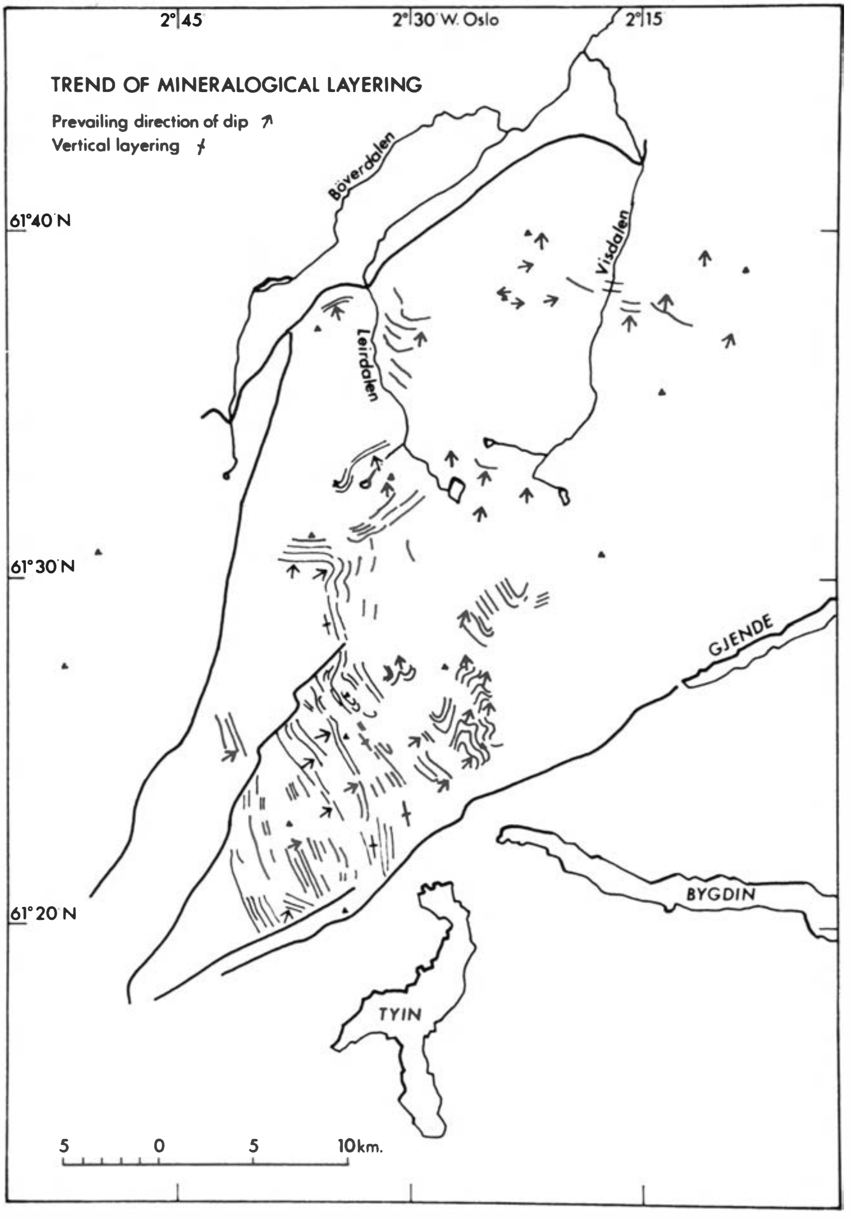

Fig. 13. Trends of mineralogical layering in pyroxene-gneisses.

pyroxene or feldspar (or olivine in the ultramafics) into layers ranging from one or two centimetres to several metres thick. It is expressed in the topography by scarps and dip-slopes resulting from differential weathering. The ultramafic layers, because of their easy recognition and resistance to erosion, give the clearest expression to the layering: they may reach tens of metres in thickness.

In the area studied, the layering is best shown in the tract of country extending north from the Tyin-Gjende Fault to Storebjörn (on the eastern edge of Smörstabbreen), bounded on the west by the Gravlöyfti Fault and on the east by a rather indefinite line passing north-east of Högbrothögdi, south-west of Mjölkedalstind, and through Rauddalsvatn to Stetind (Fig. 13).

Layering is fairly well developed in the area of Smörstabbtindane and Loftet and around mid-Visdalen.

In the tract between the Tyin-Gjende Fault and Storebjörn, the following elements may be distinguished. On the west a layered succession striking at 330° runs from around Breikvamsnosi and the ridges west and north of Koldedalen, across the head of Hjelledalen and the upper part of Morka-Koldedalen, through Falketind to the Gravlöyfti Fault south of Fleskedalen. Dips in this succession are steep and generally easterly, though sometimes to the west. Remnants of a layered succession in line with these strata occur south of Uradalen, in the faulted zone between the Gravlöyfti and Utladalen Faults.

In the belt through Koldedalen into Uradalen the strike is again about 330°. The rocks dip steeply to the east in the south, but the dip decreases to about 45°E in the upper part of the impressive succession, 1200 m thick, exposed in the south-west face of Uranostind.

Next to the east, comes the longest nearly continuous group of strata so far traced in the pyroxene-gneisses of the Jotunheimen. It extends from the southern end of Langskavlen (Rusteggen), in the south, to Gravdalstind in the north. It comprises a group of unusually thick and numerous ultramafic layers. Their continuity is by no means perfect, and there is no infallible way of correlating the sections, but the large amount of ultramafic rock in this zone, and its characteristic interbanding with feldspathic gneiss on the east of the main ultramafic outcrop, indicate strongly that it is a genetic unit.

From Langskavlen, in the south, to Rauddalen, dips in this zone are steep to subvertical. In crossing Gravdalen, however, the strike of the layering swings rapidly to westerly, with a northerly dip of 30° to 40°. The east-west strike and northerly dip persists from here northwards to Loftet and to the North-west Boundary Fault. Similar northerly dips prevail in mid-Visdalen, around Galdehöe and Skauthöe.

Throughout the zone from Langskavlen to Loftet the lineation is consistently north-westerly or northerly, and plunges south-eastwards in the south and north-westwards or northwards in the north (Fig. 11). Its conformity in direction with lineation south of the Tyin-Gjende Fault has already been noted. The reason for this is not clear, but it may be significant. Indeed, one is tempted to speculate that the abrupt southward swing of the boundary of the Jotun group (in its broad sense), to form the eastern side of the Tyin window, may have some underlying connection with the strongly-marked NNW-trending zone in the rocks north of the Fault.

Eastwards of the Langskavlen-Gravdalen Steep Belt is a tract where the

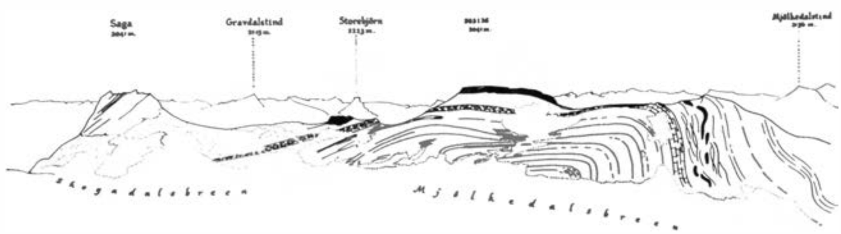

Fig. 14. View north-eastwards from Langskavlstind showing a south-east-facing fold in Dietrichson's ridge, south-east of Saga (after Battey 1965).

strike of the layering is more variable, and dips in general less steep. Immediately east of the Steep Belt the dip is north-easterly, though with minor open folds of north-westward trend. On Storegut and Mjölkedalstind the dip becomes northerly, and it continues between northerly and north-easterly in the pass between Rauddalen and Langvatn.

McRitchie (1965) suggests that there is a set of south-east-facing monoclines superimposed upon the north-westerly folds around Mjölkedalsvatn. The most impressive of these is in the ridge south-east of Saga. This ridge is the one figured by Dietrichson (1958, Fig. 6) in connection with his suggestion that Jotunheimen is a layered igneous complex. Along the ridge, rather low dips are shown towards Saga; but at the 1990 m point, about halfway along its length, the strata are intersected by a powerful fault with down-drag to the south-east, which is splendidly seen from Langskavlstind (Fig. 14). This is one of the south-east-facing monoclines; but, because of the glacier (Mjölkedalsbreen) to the west and permanent snow to the east, it has not been possible to follow the course of this disturbance on the ground or on the air photographs and little is known about it. It would be

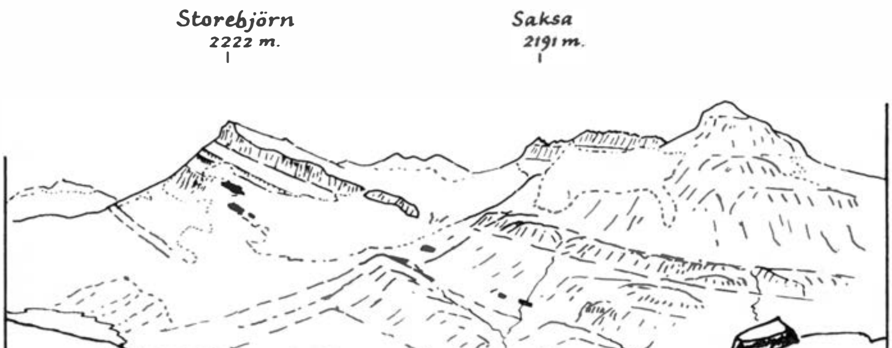

Fig. 15. Storebjörn viewed from the east, showing major lithological layering dipping northwards.

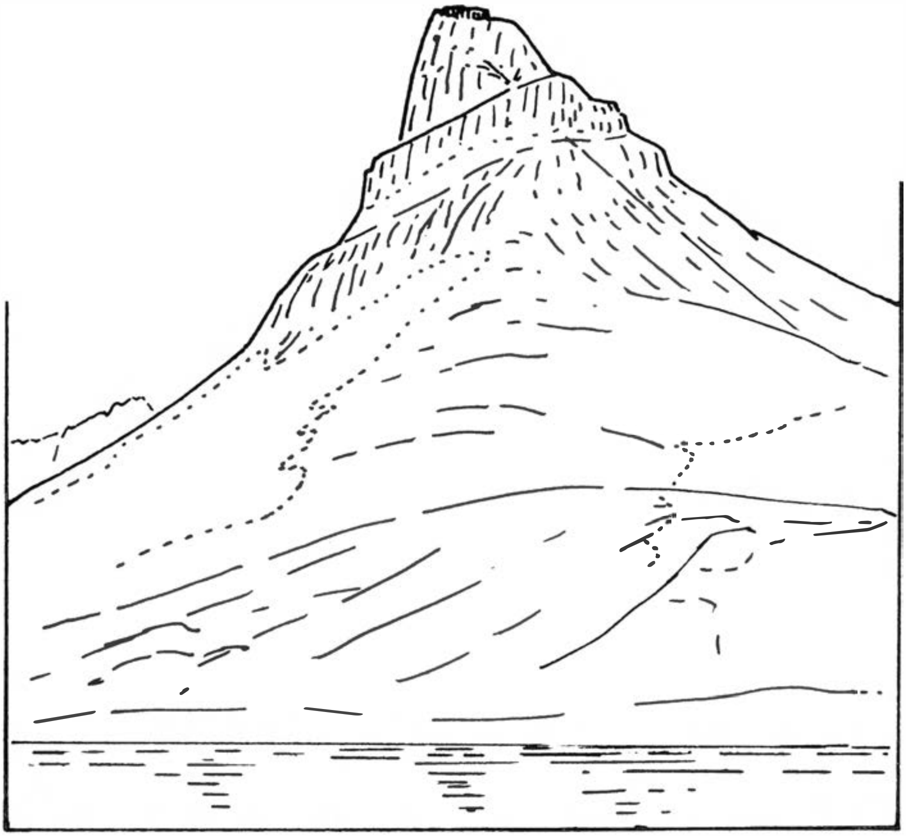

Fig. 16. Kyrkja (2032 m), at the head of Leirdalen, viewed from the west, showing the northerly dip of the major layering. The extreme summit is made of peridotite.

of great interest to examine it at close quarters to determine the metamorphic facies of the rocks involved in it.

The strata on Högbrothögdi and between Langskavlen and Mjölkedalsvatn are also bent down to the south-east, by movement on a fault that forms the northern boundary of the Tyin-Gjende Fault-zone.

South-east-facing monoclines, post-dating north-westerly folds, are also recorded from south of the Tyin-Gjende Fault (p. 249).

In the northern part of the area, from Gravdalstind and Loftet eastwards to Visdalen, the strike of the major layering is easterly or east-north-easterly and the dip northerly. This attitude prevails in Storebjörn (Fig. 15), Kyrkja (Fig. 16), the north slope of Visbretind, and around Galdehöe and Skauthöe in mid-Visdalen. It is also suggested by a few observations between Leirdalen and Visdalen (on Bukkeholstindin and Uladalstind). There are, however, large areas between Leirdalen and Visdalen for which no information is available. No continuous belt of distinctive rocks has so far been recognised in this area, to compare with the Langskavlen-Gravdalen Belt.

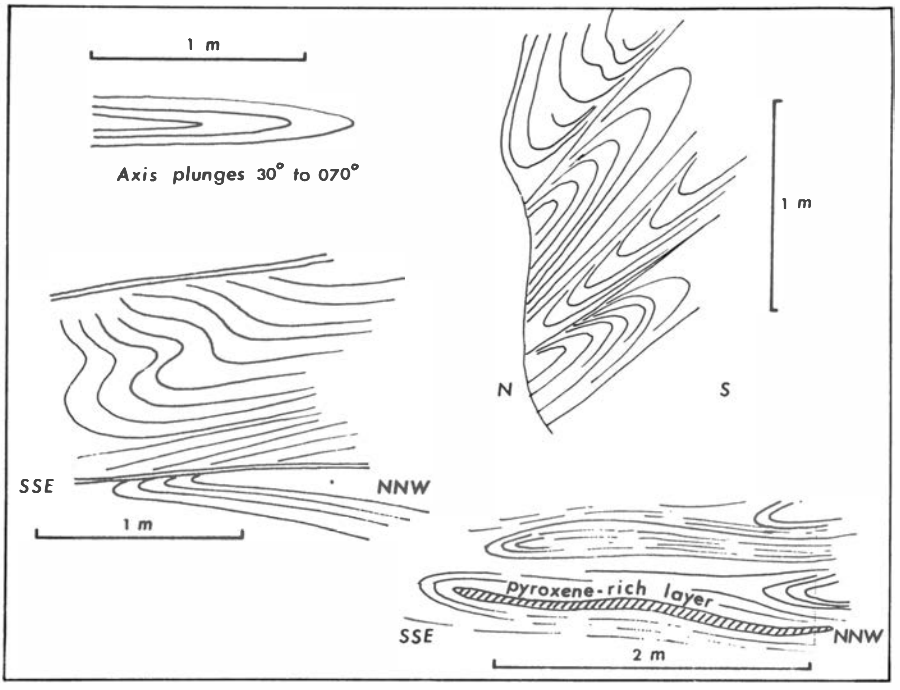

Fig. 17. Minor folds in pyroxene-gneiss in Gravdalen. Lines indicate the traces of the pyroxene folia.

Minor folds

Detailed study of the mineral folia in Gravdalen shows that, although the major layers have a fairly consistent attitude, the folia within these layers are folded into highly-compressed isoclines, like those illustrated in Figs. 17 and 18, with closures directed east and west. Mesoscopic folds are also developed, though the lack of distinctive horizons on an appropriate scale makes them difficult to trace out.

Poles to foliation planes and lineations measured in Gravdalen are plotted stereographically in Fig. 19, which shows that the minor folds plunge north-north-westwards at about 30°. If the rule applies that minor folds reflect the form and attitude of the major folds, the testimony here is that the major folds are reclined, with both limbs and the fold-axes inclined downwards to the north.

There are also some minor folds with axes plunging east-north-eastwards at moderate angles, and the occurrence of minor folds with closed ellipsoidal traces on smooth surfaces indicates the probability of repeated folding, which requires more intensive study of limited areas for its elucidation. Areas well-suited to such geometrical studies are abundantly available, especially where the recent retreat of glaciers has exposed extensive areas of bare rock.

At the present time, the point that seems clearly established by the trend

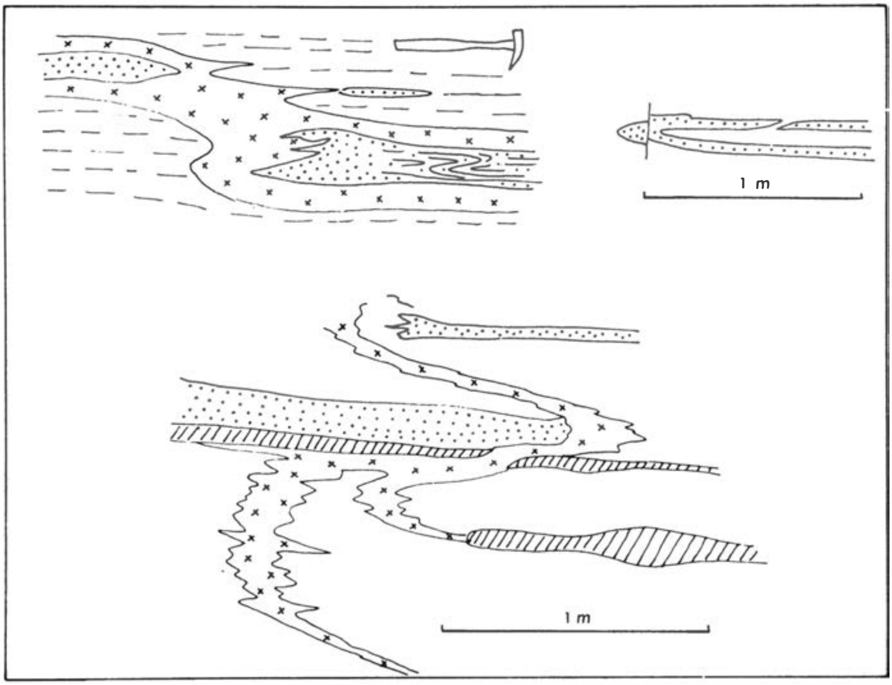

Fig. 18. Pull-apart structures and feldspathic veining in Gravdalen. Dashes denote pyroxene folia, dots pyroxene-rich layers, diagonal lines pyroxenite and crosses feldspathic rock.

of the outcrops, the orientation of the lineation, and the attitude of foliation planes is that a north-westerly fold-axial trend is dominant in the pyroxene-gneisses of the central Jotunheimen. This trend has long been known in the South Norwegian Caledonides (the 'transverse trend' of Landmark 1949, p. 56), and its existence has recently been re-emphasised by Loeschke & Nickelsen (1968).

As the rocks affected by the north-westerly folding are not retrogressively metamorphosed from the condition of pyroxene-granulites, although folding was intense, it is clear that the deformation took place under pyroxene-stable conditions, with high temperature and pressure. These conditions are different from those that have prevailed in the rocks assigned to the Jotun stem south of the Tyin-Gjende Fault. This seems to indicate that whilst the rocks south of the Fault were being deformed in the amphibolite and greenschist facies, the pyroxene-granulite facies rocks were either protected in some way, or were (then or later) passively carried to their present position.

Pegmatitic veins

In the area of Gravdalen and Leirvassbu, numerous vertical granite-pegmatite veins, striking east-north-east, cut the pyroxene-gneisses (Fig. 3). Some

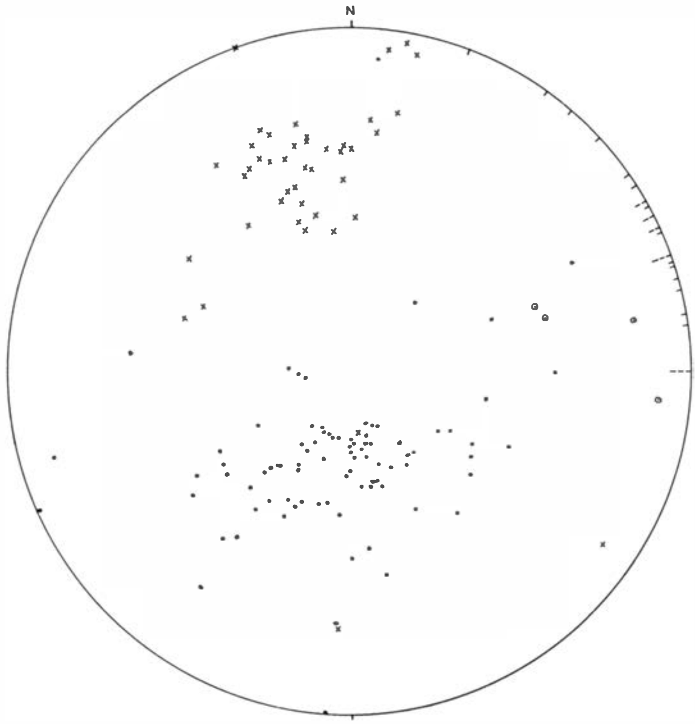

Fig. 19. Stereogram (lower hemisphere) of structural elements in Gravdalen. Crosses indicate lineations, dots poles to foliation, circled points fold axes, and short dashes the azimuths of pegmatite veins.

of these have been followed for up to 2 km in this area. A most striking example may be observed from the path between Spiterstulen and Leirvassbu, as it traverses upper Visdalen. The vein runs down the east-facing wall of the cirque Tverrbyttnede at a point 8 km on 197° from Galdhöppigen summit and is sketched in Fig. 20. These veins represent a late stage of injection, probably later than the uplift of the gneisses. Veins with the same trend in the Mjölkedola Gabbro are earlier than the thrusts cutting the gabbro (Fig. 12).

Chronology of the Jotun rocks

Goldschmidt regarded the Jotun rocks as upthrust during the Caledonian fold-movements, and their erosion was supposed to have yielded debris, including characteristic mesoperthite crystal-fragments, to the Valdres Sparagmite formation. On the hill Mellene, 55 km east-south-east of Tyin, the Valdres Sparagmite was supposed to overlie the Mellsenn Group which contains Lower Middle Ordovician graptolites. The Mellsenn Group is in turn thrust over the Phyllite Formation with older graptolites. Since the Valdres Sparagmite was thought to be younger than Middle Ordovician, there

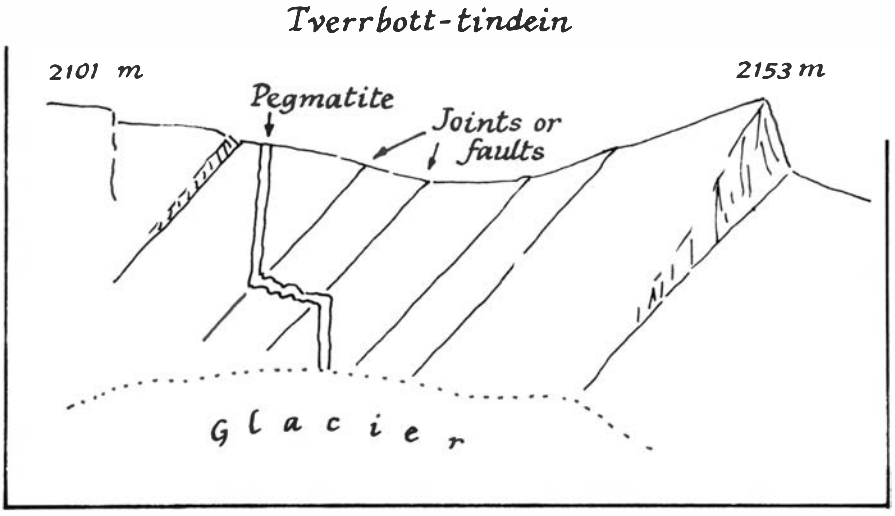

Fig. 20. View westwards from upper Visdalen to the eastern wall of Tverrbott-tindein showing a strong vertical ENE trending pegmatite vein.

was no evidence that the Jotun rocks had been brought to the level of erosion before that time, and the idea of their emplacement by intrusion and thrusting during the opening phases of the Caledonian orogeny was proposed, and for many years was accepted.

Loeschke (1967a, b) and Nickelsen (1967) have now shown, however, by means of sedimentary structures, cleavage-bedding and drag-fold relations, that the Valdres Sparagmite and Mellsenn Group are inverted, though stratigraphic continuity between them is confirmed. The Valdres Sparagmite, now *below* the Mellsenn Group, is more than 3000 m thick, and its base is not seen on Mellene. On the hill Grönsennknipa, 50 km south-east of Tyin, the unfaulted base of the Valdres Sparagmite rests unconformably upon granite with included gabbro blocks (Hossack, in press) assigned to the Jotun group. Nickelsen concludes that the Valdres Sparagmite is Eocambrian in age in its lower part, and that both it and the Jotun rocks were thrust to their present position after Eocambrian deposition of the Valdres Sparagmite upon eroded Precambrian Jotun rocks (1967, p. 117).

Within the Valdres Sparagmite, on Mellene, fold axial-planes dip NE, and fold-axes are arcuate, with NW or SE plunge in the north-western part of the area, and NE plunge in the south-east. Overturning is towards the SW, S, and locally SE. On Grönsennknipa axial planes dip NE and fold-axes plunge SE (Nickelsen 1967, p. 120).

The NW or SE plunges of fold-axes conform with the plunge of lineations in epidote-amphibolite facies rocks south of the Tyin-Gjende Fault, and in pyroxene-gneisses north of it. It would, perhaps, be premature to attempt to draw conclusions from this fact at present. Much more structural data on the Jotun rocks is required. Nevertheless, allowing for regional differences in depth of burial during folding, it might be suggested that the

Table 1. Potassium-argon ages of Jotun minerals.

Rock No.	Location	Material analysed	K/A age (m.y.)
58/20	1.25 km on 110° from Mjölkedalstind	Feldspar from pyroxene gneiss	435 ± 13
58/21	1.75 km on 110° from Mjölkedalstind	Feldspar from pyroxene gneiss	462 ± 10
58/23	Rauddalen, 0.5 km on 220° from Olavsbu	Feldspar from pyroxene gneiss	428 ± 8
58/24	Semmeldalsmunnen, 3.5 km on 20° from Olavsbu	Feldspar from pyroxene gneiss	475 ± 14
58/26	Presten ridge, N of Leirvassbu	Feldspar from pyroxene gneiss	1020 ± 40
65/26	S.E. end of Presten ridge N. of Leirvassbu	Feldspar from dark poorly-foliated pyroxene gneiss (? early dyke)	640 ± 12
62/120	Mjölkedola area (exact location unknown)	Feldspar from biotite-rich pyroxene gneiss	640 ± 12
J34	Visdalen 2.5 km on 40° from Spiterstulen	Hornblende from ultramafic body	666 ± 20
64/2	Store Utladalen 3.5 km on 210° from Gravdalstind	Feldspar from biotite adamellite vein trending 41°	1280 ± 30
64/2	Store Utladalen 3.5 km on 210° from Gravdalstind	Biotite from the same	452 ± 8

Analyst: Dr. J. G. Mitchell. School of Physics, University of Newcastle upon Tyne.

NW-SE lineations and fold-plunges in Jotun basement and Eocambrian-Lower Palaeozoic cover represent response to the same system or episode of Caledonian movement.

Potassium-argon age determinations have kindly been carried out by Dr. J. G. Mitchell on feldspar from pyroxene-gneisses from the central Jotunheimen. His results are given in Table 1. There are two high ages, one of which (64/2, feldspar) is in disagreement with the age from biotite in the same rock. For the rest, the results show that there has been a metamorphic or metasomatic event, at the time of the Caledonian orogeny, that released argon and reset the K/A clock, under pressure and temperature conditions that allowed the pyroxene-granulite facies mineralogy to remain stable.

On the other hand, rocks correlated with the Jotun group were at the surface in Precambrian times, to receive an unconformable cover of Valdres Sparagmite, that has never been above greenschist facies pressures and temperatures.

If the Jotun stem rocks are to be regarded as a single unit, the situation just outlined requires that the unit is immensely thick, and spanned a wide range of pressure-temperature conditions during the Caledonian orogeny.

There are strong grounds, however, for dividing the original Jotun stem rocks into two main groups. One group comprises the pyroxene-gneisses of the central (axial) region of the outcrop, north of the Tyin-Gjende Fault. These are metamorphic rocks, recrystallized under granulite facies conditions. Their high grade metamorphic nature is never clearly brought out in Goldschmidt's descriptions, where they are referred to as Jotun norites, hypersthene-syenites etc., but is known from later investigations (Battey 1960, Griffin 1971, McRitchie 1965).

The other group is one of gabbros, syenitic and granitic rocks, peripheral to the pyroxene-gneisses. They show no evidence of having been metamorphosed in the granulite facies, though many are in the condition of amphibolites. The gabbros may show relict igneous textures, including ophitic texture, as Goldschmidt clearly described. He recognised this group as forming a border facies of his 'Jotun norites', especially south-east of the axial region of the Jotun outcrop. He regarded them as in some cases older than his Jotun norites; but detailed evidence for this is not given. In the present survey, one dyke of ophitic dolerite, or microgabbro, has been found cutting the layered pyroxene-gneisses on the south slope of Storegut, 1.3 km on 172° from the summit. This single example implies that there was also a gabbroic magma younger than the pyroxene-gneisses.

Peripheral gabbros have been recognised around both the northern and southern margins of the pyroxene-gneiss tract. The task remains of tracing them further around its borders, and perhaps of locating more intrusions of gabbro within the pyroxene-gneiss tract.

The pyroxene-gneisses, as far as is known, are always in faulted contact with the peripheral group, and must have had a very different history from them. The Grönsennknipa evidence for surface exposure and erosion of Jotun rocks in Eocambrian times would apply only to rocks of the peripheral group. It is therefore quite possible that the rocks of the pyroxene-gneiss group were not exposed in the Eocambrian, and then reburied by the Valdres Sparagmite and later strata, but were upthrust from the depths at the time of the Caledonian orogeny. This would accord better with the preservation of their high-pressure high-temperature mineralogy.

The fundamental distinction between the two proposed groups is that the peripheral group would have been emplaced magmatically at relatively high level, and would have been metamorphosed in the epidote-amphibolite facies during the Caledonian orogeny; whilst the pyroxene-gneiss group received its metamorphic imprint at great depth and was tectonically emplaced, with only local retrogressive metamorphism in the Caledonian. The deep root shown by the gravity profile is associated with this upthrust block, while the south-easterly, geophysically thinner area of dense rocks represents the magmatically-emplaced group.

As noted above, the ophitic dolerite dyke on Storegut implies that some of the gabbroic magma was injected during, or after, the uprise of the pyroxene-gneisses. This in turn would mean that the magmatic group was not all pre-Eocambrian. But the diversity of the peripheral group, which includes aegirine-granites in places, makes it likely that more than one magmatic episode is involved. Metadolerite dykes cutting thrust sheets of retrogressively metamorphosed gabbro east of Tyin also testify to a more than one episode of basic magmatism. Members of this set of dykes, discovered by McRitchie (1965), are shown in Fig. 8. He has also found that they occur around the east end of the lake Bygdin. These dykes may well prove to be of great importance in further study of the chronology of the Jotun rocks.

Late basic magmatism may, therefore, well have accompanied and lubricated the uprise of the pyroxene-gneisses.

From the foregoing, the following tentative sequence of events may be derived, as a basis for further study.

1. Pyroxene-granulite facies metamorphism of the rocks north of the Tyin-Gjende Fault. These must have crystallized initially at pressures in excess of 8 kb and finally above 4 kb. The date of this event is not known.
2. Emplacement of granite with gabbro inclusions on Grönsennknipa. With this may be correlated the intrusion of some parts of the peripheral zone of gabbros and granites north, and especially south-east of the pyroxene-gneiss zone. It is not possible, at present, to specify which units of the peripheral group were emplaced at this time.
3. Erosion interval.
4. Deposition of the Valdres Sparagmite and succeeding beds of the Mellsenn Group from Eocambrian to Middle Ordovician times. They rest unconformably on the granite with gabbro inclusions on Grönsennknipa.
5. (a) Folding and overturning of the Valdres Sparagmite and the beds above it.
   (b) With this may be associated the thrusting of the peripheral gabbro sheets to a position above the Valdres Sparagmite at Bygdin, in the upper Bövra and elsewhere, and the thrusting of varied gabbro and granite sheets east of Tyin.
   (c) Pegmatite injection accompanied this thrusting.
   (d) Tectonic emplacement of the pyroxene-gneisses, bounded by thrust faults. This would correspond with the decompression inferred by Griffin (1971) on mineralogical grounds. At higher levels, lag faults formed which retrograded the pyroxene-gneiss to amphibolite facies assemblages. On the evidence of metamorphic grade, these may have been co-eval with the thrusting around the borders of the pyroxene-gneiss area.

   East-north-easterly, vertical, quartzo-feldspathic veins are cut by the thrusts in the Mjölkedola Purple Gabbro. These veins may be correlated with those around Gravdalen and Leirvassbu, in the pyroxene-gneiss tract. Thus some part of the thrusting (and associated pegmatite formation) post-dates a tensional phase that followed the emplacement of the pyroxene-gneiss core.

(e) Metadolerite dykes cut the thrust sheets east of Tyin and one cuts the pyroxene-gneiss core. Those east of Tyin antedate part of the thrust movement.

6. Late faults that cut the lag faults (e.g. in Galdenhöe cirque) have epidote and porphyroblasts of potash feldspar along them. In metamorphic grade these are similar to retrograded rocks along the Tyin-Gjende Fault. There may therefore have been a late phase of movement along this fault, and perhaps along the Utladalen and Gravlöyfti Faults.

In the course of the events comprised under 5.(d) above, the temperature exceeded the sealing temperature against argon loss (about 300°C), in the pyroxene-gneiss area, and the K/A clock was re-set, or partly re-set, so that these rocks yield radiometric ages mostly between 660 and 430 my.

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May 1972

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