# *Layered structure in rocks of the Jotunheim Complex, Norway*

With Plates III and IV

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*Summary.* Two-pyroxene feldspar gneisses and associated ultramafic rocks of the Jotun Kindred in Southern Jotunheimen display mineralogical layering believed to be of original igneous origin. The geological structure of part of the stratiform massif is described, and is shown to provide a basis, hitherto lacking, for systematic study of the mineralogical and chemical variation of the suite.

## *Introduction*

THE opportunity to make his first visit to the Jotunheim was offered to the writer as a student under Professor Tilley at Cambridge. For this introduction to a field that has since provided him with sustained interest the writer is deeply grateful. A number of visits in succeeding years emphasized the need for elucidation of the field relationships of the rock-types as a condition of their systematic study. With the selection, in 1958, of the area north of Eidsbugarden as favourable ground, and with the use of aerial photographs in 1962, it became possible to recognize and map the stratification reported in this paper.

## *Previous work*

The petrological study of the rocks of Jotunheimen began with the classic paper by Goldschmidt (1916) in which he proposed the establishment of the Jotun stem or kindred. This was based upon his own field observations and those of Survey workers, especially K. O. Björlykke and Rekstad, together with a wealth of petrographic detail and numerous chemical analyses. Goldschmidt recognized the unity of the rock types from the wide area of Jotunheimen as comprising variations in the proportions of three principal minerals, basic plagioclase, potash feldspar (perthite), and pyroxene, with anorthosite, microperthite rock, and pyroxenite as end members, while Jotun-norite and mangerite were the more abundant intermediate representatives.

The term jotunite has since been proposed (Hödal, 1945) to cover rocks of intermediate type in Goldschmidt's nomenclature. This suggestion is welcome, since the original nomenclature is perhaps too closely linked with that of igneous petrology. It is a fact insufficiently emphasized that a large part, perhaps the majority, of the rocks of the High Jotunheim are metamorphic types. This is not easily gathered from Goldschmidt's memoir, where the rocks are classified under igneous names and their textures are not described in detail. In fact, however, in the interior parts of Jotunheimen, from a little north of Eidsbugarden in the south to Galdehö and Trollsteinkvolven in the north, and from Smörstabbtindan on the west to Glitterheim and south-eastwards towards Gjende on the east, the rocks show mineralogical foliation or lineation and their textures indicate clearly that they have recrystallized under metamorphic conditions (plate III, figs. 1 and 2). Their mineral composition indicates that these conditions were those of the granulite facies.

Goldschmidt (p. 26 et seq.) did, however, clearly separate a group of 'normal' norites and gabbros from the main mass of his Jotun-stem rocks. These normal types display ophitic (diabasic) texture in places and were regarded as, in part, an older border facies of the Jotun-norites (p. 28). Goldschmidt considered that they were in close genetic connexion with the Jotun-norites proper.

Rocks of gabbroic or noritic mineralogy that retain their igneous texture occur around Eidsbugarden in close association with gneissic jotunites, a fact that gives this area particular interest and led to its selection for further study.

Although their present metamorphic condition requires emphasis, there is every reason to believe that Goldschmidt was correct in assigning an original igneous history to the gneissic jotunites, and it is with the character of the original igneous body in which they formed that the present paper is concerned.

Since Goldschmidt's memoir few publications concerned with Jotunheim petrology have appeared. Carstens (1920) described the general features of the peridotite members of the complex, and attributed them to early crystallization of olivine accompanied by pyroxene at separated points, due to local pressure–temperature changes. This early crystallization ceased when the residual liquid reached an anchi-eutectic pyroxene-feldspar composition and noritic or gabbroic rocks crystallized enclosing the ultramafic bodies.

The present writer (Battey, 1960) studied the relationships of some of the ultramafic bodies, and concluded that the problem of their origin must be solved in the light of further work on the variation in the enclosing granulites, but tentatively adopted the view that they were intrusions into the latter. The further work on the enclosing jotunites, reported in this paper, suggests that the alternative hypothesis, that the ultramafics, and the rest of the gneisses, are products of igneous sedimentation, is correct. There remain a number of contact features that support the previously-held view of intrusion, but these appear to be outweighed by the evidence of an overall stratiform structure.

Dietrichson (1958) had already suggested, as we now believe correctly, that the Jotunheim rocks represent an original layered igneous intrusion. The basis of his deduction was, however, far from strong. He supported his suggestion by reference to a collection of chemical analyses taken from the literature, supplemented by five new ones, which he plotted on variation diagrams (silica versus other oxides). This type of evidence cannot, by itself, be in any way conclusive of a stratiform (or any other) structure in the complex from which the samples have been taken. The only piece of evidence of such structure in Dietrichson's paper is his fig. 6 showing layering in the flanks of 'Mt. Saga' (actually the ridge to the south-east of Saga); but this figure is not referred to in the text.

The present paper outlines the results of geological mapping of a stratified succession of jotunites around Mjölkedalsvatn near the western end of Lake Bygdin (fig. 1), and provides conclusive evidence that at least part of the Jotunheim complex is a stratiform massif. This evidence, in conjunction with the chemistry and petrography of the rock units, indicates strongly that this part of the region is a layered igneous intrusion that has been subjected to subsequent folding and metamorphism.

## *Outline of the geology*

Eidsbugarden, at the western end of Lake Bygdin, is some four kilometres inside the great boundary thrust of the Jotunheim massif. This boundary lies to the west where, north of Lake Tyin, the outcrop of the dislocation between the Valdres Sparagmite Formation and the Jotun rocks turns abruptly through 90° and, having followed a north-easterly course on the north-west of Tyin, runs south-south-eastwards to disappear beneath the waters of the lake. Its further continuation eastwards is 16 km south of Eidsbugarden. The area to be described thus lies entirely within the Jotunheim overthrust sheet, though its southerly part is a relatively short distance from the thrust-plane.

The geology of the area (fig. 2) is sharply divided into two parts by an important fault which may be traced from north of Lake Tyin (at the bend in the boundary thrust just mentioned) east-north-eastwards for 16 km to Lake Gjende, with a probable further extension in both that direction and to the south-south-west. This major fracture we propose to call the Tyin–Gjende Fault.

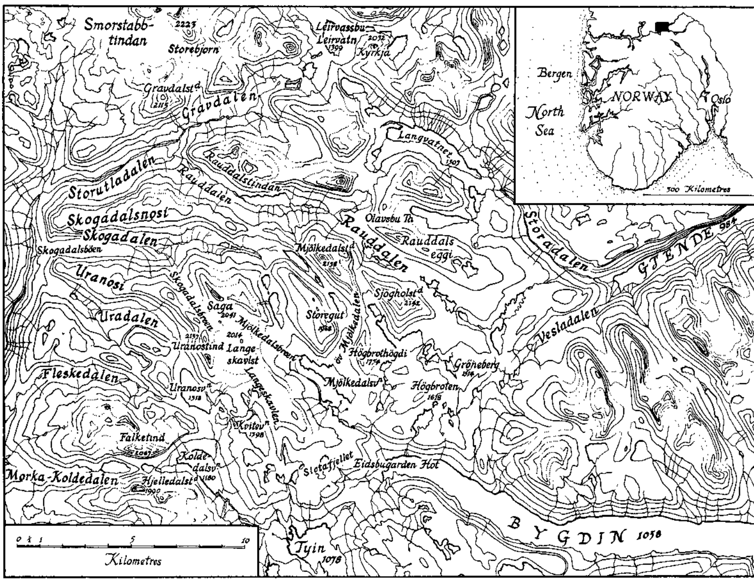


FIG. 1. Area of investigations in Jotunheimen.

South of this line, in the area studied, the ground is largely occupied by a gabbro of a predominantly purple tint which, in parts, retains its igneous texture. This, in its various phases, we designate the Mjölkedola Purple Gabbro, from the Mjölkedola Valley locality at Eidsbugarden, where it is excellently exposed, and which furnished a number of Goldschmidt's and Schetelig's specimens.

North of the Tyin–Gjende Fault the rocks are of gneissic character, true jotunites, that here exhibit an excellently developed stratification, in which continuous sections in excess of 1000 metres thickness are available, as for example on Högbrothögdi. These rocks constitute the Layered Sequence.

A third group of rocks comprises the mylonites and retrogressively metamorphosed types associated with the main fault-lines.

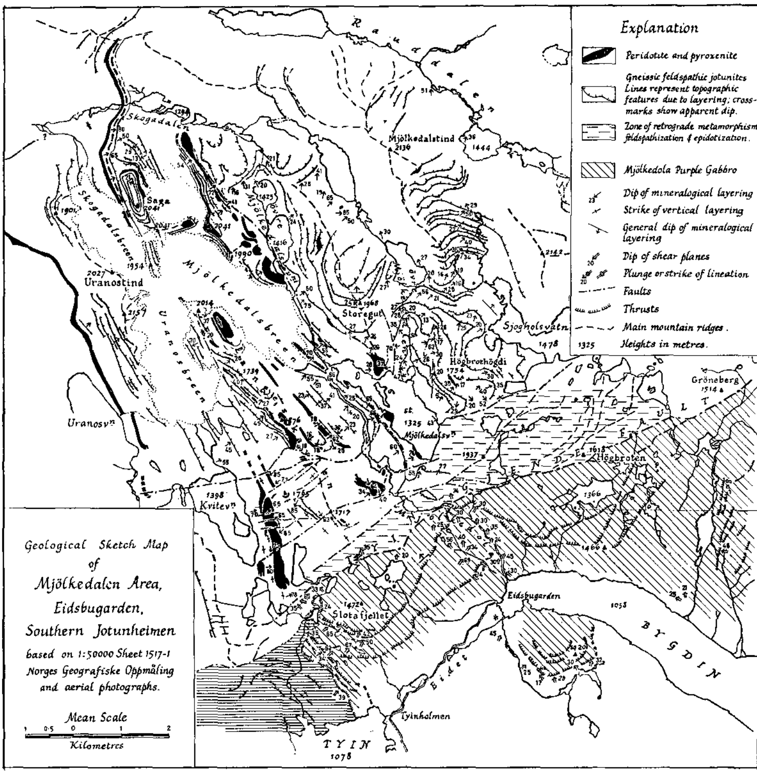


FIG. 2. Geological map of the Mjölkedalen area.

## *The Mjölkedola Purple Gabbro*

*Distribution.* This group of rocks is bounded to the north by the Tyin–Gjende Fault and occupies the ground on the south side of this line from Slötafjell in the south-west, north of Lake Tyin, to Gröneberg, and the south-western slopes of Tungepiggan, nearer to Gjende, in the north-east.

On the south-western slopes of Slötafjell it becomes highly sheared and is bounded by the main Jotunheim thrust above the Valdres Sparagmite.

To the south its boundary is not well established. It appears to terminate in the south-south-easterly slopes of Slötafjell above finely foliated and strongly tectonized crystalline rocks of uncertain origin that underlie Eidet, the isthmus between Lakes Tyin and Bygdin. Isolated exposures of Purple Gabbro are known to occur farther south, however, along the eastern shore of Lake Tyin some 4 km from Tyin Hotel, where it is interesting to note that they are spatially closely associated with outcrops of the aegirine granite found by Björlykke and described by Goldschmidt (1916, p. 50). At the western end of Lake Bygdin, on its southern side, a sheet of Mjölkedola Purple Gabbro veneers a small area of the slope descending to the lake, being separated from underlying gneisses of uncertain status by a dislocation plane occupied by a sheet of pegmatitic feldspar-rock. On the north shore of Lake Bygdin 3·5 km from Eidsbugarden highly sheared platy rocks of gabbro-schist type crop out in the valley side below Purple Gabbro, which is found in the upper slopes.

The Purple Gabbro extends eastwards into the slopes of Uksedalshö and Rundtum, east of the Eidsbugarden–Gjendebu track; but its further extension in this direction has not yet been followed.

*Petrography.* Although this gabbro retains an ophitic igneous texture in many outcrops, it has been subjected to dynamic stresses that have induced a foliation in many places. Even in the foliated condition, however, it generally remains distinguishable without difficulty from the foliated jotunites north of the Gjende–Bygdin Fault.

In thin section some specimens show excellent coarse ophitic structure indicative of their magmatic crystallization. They are composed essentially of plagioclase ($An_{40}$), orthopyroxene, and clinopyroxene, with magnetite and apatite as accessories, a typical gabbroic assemblage. The effects of later metamorphism are shown in the marked clouding of the plagioclase by opaque dust, whilst the pyroxene is also clouded by minute dots of magnetite. Where intergrowths occur, the orthopyroxene is less clouded than the clinopyroxene. The pyroxene and iron ore both show excellent coronas, those around the pyroxene being of hornblende and garnet, and those around the ore of biotite and garnet. Iron ore is in part converted to green spinel, and plagioclase to scapolite in some cases.

The metamorphism is regarded as dynamic in character as is evidenced by the development of foliation over considerable parts of the outcrop area, and by the presence of a series of low-dipping movement planes, commonly occupied by pegmatitic feldspathic rock, which traverse the main part of the gabbro. These are well shown on Slötafjell and in Mjölkedola River. In the Mjölkedola the rock, composed of black pyroxene and purple feldspar, is on the whole very uniform and without foliation or fissility in hand specimen, though there is some mineralogical segregation in places, and fine-grained bands occur, sometimes with sharp margins, probably due to shearing. There are also streaks and areas where saussuritization of the purple feldspar gives white flecked rock on the weathered surface. A patchwork of white and purple areas is sometimes developed. Well-developed planes of shearing cross the Mjölkedola, conspicuously filled with feldspathic rock that has a pronounced streaky banding dipping in conformity with the sheet of light-coloured rock. The neighbouring purple feldspar rock is rendered white-flecked and streaky. Associated with these low-dipping pegmatitic sheets are some vertical quartz-feldspar dykes or veins a few cm to 30 cm wide.

Possibly of the same period of origin as these features are very numerous surfaces of movement striking north-north-east and dipping west that define a series of low ridges south of Gröneberg in the eastern part of the area studied.

The plane occupied by pegmatite below the veneer of gabbro on the south side of Bygdin at its western end may be cognate with the pegmatite-filled movement planes in Mjölkedola River bed.

These low-angle dislocations recall those occurring in true jotunites around Spiterstulen in Visdalen, North Jotunheim, at no great distance above the Jotunheim boundary thrust (Battey, 1960*a*, p. 199; 1960*b*, p. 7).

A second type of dynamic action on the gabbro is localized along and near the Tyin–Gjende Fault. Here the gabbro is converted to a dense flinty mylonite of a greenish shade, with dark shreds of flinty crush rock, which is resistant to erosion and forms a ridge along the south side of the fault for much of its length. These mylonites are well exposed for study in the ridge immediately north of Slötatjern, 2·5 km west-north-west of Eidsbugarden Hotel, from whence also an excellent view of the fault feature is obtained.

### *The layered sequence*

The rocks forming this sequence are two-pyroxene granulites, pyroxenites, and peridotites with a marked foliation, and often a lineation produced by the alignment of pyroxene crystals. The layering that they exhibit is produced by variations in the proportions of the total dark silicates (orthopyroxene, clinopyroxene, and biotite) to feldspar in the granulites, and of olivine to pyroxene in the ultramafics.

The units of layering vary in thickness from tens of metres for lenses of ultramafic rock or the more persistent feldspathic granulite layers to subdivisions a decametre or so thick, traceable laterally for tens of metres within the larger units (plate IV, fig. 2).

The strata produced by this variation in mineral proportions form prominent ledges and show a regularity of structural behaviour which enables them to be used as mapping units. The layered sequence has so far been studied in the region extending north of Lakes Tyin and Bygdin to Rauddalen, and from Uradalen in the west to Sjogholstind in the east (Map-sheet Norge, 1:50000 1517–1, Tyin). With the aid of aerial photographs it is possible to trace the outcrop ledges of the layered rocks with confidence throughout this area, and to make estimates of the amount and direction of their dip. The attitudes and lithologies of the layers have been confirmed on the ground over most of the area, and the information plotted on the map (fig. 2). The outcrop ledges have been drawn from aerial photographs, while the dips recorded are the result of measurements on the ground. This reconnaissance mapping is being followed up at present by detailed work in the Mjölkedalsvatn basin by W. D. McRitchie.

The general picture that emerges is that of a succession with a regional strike of about N. 40° W., broken up into strips by powerful lines of dislocation trending north-west, along which the strata are dragged into a sub-vertical attitude. Between these disturbances the layers are thrown into open folds of the order of 1000 m across the axis. The folds are cut by a series of faults running between north-east and east, most of which appear to be quite small, in that the steeper beds may sometimes be traced across them with little displacement.

In the absence of good marker horizons, however, it is not possible, as yet, to make correlations between the successions in the layered rocks separated by the larger faults, or to estimate the amount of movement on these. It is hoped that when the changes in compositions of the minerals through the thickest available continuous successions of the layered rocks have been investigated, these will provide a means of estimating broadly the relative positions of the various fault-bounded blocks.

*Major lines of dislocation (the steep zones)*

The lines of steep layering due to faulting or intense, abrupt downwarping that form the boundaries between the main structural divisions so far recognized are now to be described.

1. *Langeskavlen–Saga–Rauddalen disturbance.* This is the most pronounced and continuous steep zone. It is marked by a concentration of ultramafic rocks, and extends for more than 15 km from Rusteggi, the large peridotite mass east of Kvitevatn, close to the Tyin–Gjende Fault, along the west side of Langeskavlen, past Saga, across Skogadalen,

and across the mouth of Rauddalen. It continues northwards, but has not been followed farther in this direction.

To the west of this line little detailed work has been done, but it is clearly established that a regional east-north-east dip at angles varying up to 40° prevails in the Uradalsvatnet–Uranostind–Uranosi zone and attention may be drawn to the excellent section through over 1000 m of the Layered Sequence that is available on the south-west slopes of Uranostind and Uranosi. Along the Rusteggi ridge the contact of ultramafic and feldspathic jotunite stands vertical. On the east side of Langeskavlen, especially on the slopes above Uranosbreen, the layering in the jotunites is vertical with a strong north-north-west lineation, cutting sharply across the more gently inclined layering on the crest of Langeskavlen. In its trace down the south wall of Skogadalen, the steep zone is marked by a massive peridotite, which is followed eastwards by interlayered ultramafic rock and feldspathic gneisses, the two units together being some 60 m thick. This interlayered zone is closely similar to that recorded lying stratigraphically above a thick ultramafic layer 2·5 km north-east of Spiterstulen, Visdalen, Mid-Jotunheimen (Battey, 1960*a*, p. 204). In Skogadalen the steep ultramafic belt cuts abruptly across the more gently dipping layers in Saga (fig 3*b*).

2. *Övre Mjölkedalsvatn line.*[1] A vertical belt runs south-east from Skogadalen, up the ridge next eastwards from Saga, and has been traced to a point overlooking the north-west corner of övre Mjölkedalsvatn. The probable continuation of this line is seen in the southern outlet of these lakes between the snout of Mjölkedalsbreen and the south-west slopes of Storegut, where the gneiss layers are vertical and powerfully compressed and drawn out.

A further steep belt, with dips of up to 76° to the north-east, runs along the south-west side of store Mjölkedalsvatn, to within a few hundred metres of the Tyin–Gjende Fault. Owing to the presence of moraine, and the glacier snout, no connexion has been proved with the övre Mjölkedalsvatn line, but it seems probable.

This zone is also marked by steeply dipping ultramafic bodies along parts of its length.

3. *Another fault* is impressively exposed in the ridge north-east of Mjölkedalsbreen, and may be magnificently viewed from Langeskavlstind

[1] The Mjölkedalen drainage is complex, because of changes due to glacial recession. On 1:50000 sheet 1517–1 övre Mjökedalsvatn lies west of Storegut (lakes at 1425 m and 1416 m on fig. 2) whilst övre Mjölkedalen lies east of Storegut. Övre Mjölkedalstjörni, lying between Storegut and Mjölkedalstind, are different again, and actually drain into Skogadalen.

(fig. 4). This ridge is that shown in Dietrichson's photograph (1958, fig. 6, p. 29) and mistakenly described by him as Saga; but in that photograph snow obscures the structure. The continuation of this fault in both directions is obscured by permanent ice, so that its relationships to other disturbances, and even its exact trend, are not known. It displays excellently, however, the effects of these structures in cross-sectional view. The dismemberment of ultramafic rocks caught in the movement plane is beautifully shown.

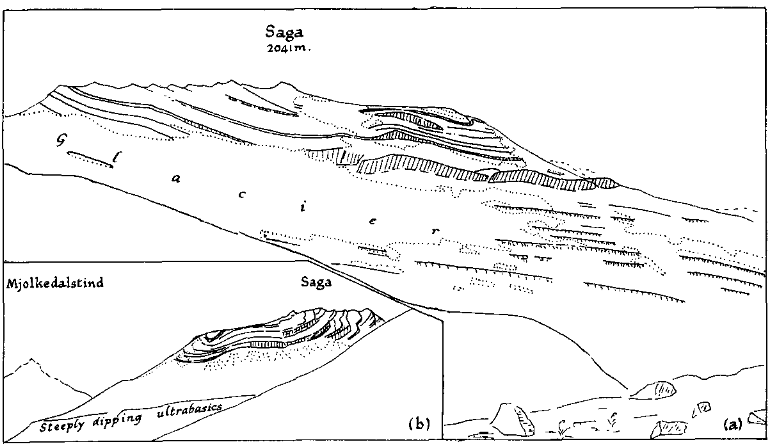


FIG. 3. Saga from the north-east (*a*), and from the west (*b*), showing stratification and folding.

Less extensive lines of steep strata, representing minor disturbances, have been mapped on either side of övre Mjölkedalen, between Storegut and Högbrothögdi.

## *The zones of open folding*

1. *Saga Ridge* (fig. 3). The ridge is flanked on the west by the steep zone incorporating ultramafics, already mentioned, which traverses a topographic shelf above Skogadalsbreen. The ridge itself is built of a narrow partial syncline of strata, like the prow of a canoe pointing south, with the west limb of the structure partly removed by erosion and perhaps involved in the steep zone. There is a gentle northward axial plunge. In the ridge to the south-east of Saga the strata run in a gentle arch along the south-west face of the ridge (fig. 4) until they are abruptly dragged into a vertical attitude at the 1990 m summit.

North-eastwards from this face the beds steepen progressively towards the övre Mjölkedalsvatn line of disturbance, so forming an anticline with a north-west trending axis complementary to the Saga syncline.

In the west wall of the övre Mjölkedalsvatn corrie the dip is 45° or more to the north-east, and the dark ultramafic rocks forming the dip-slope here are partially stripped by erosion from the underlying pale gneisses, to give a striking and complex pattern of dark- and light-coloured rocks when viewed from the slopes of Storegut.

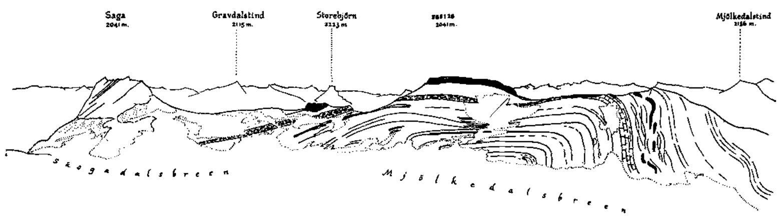


FIG. 4. View north by east from Langeskavlstind. Ultramafic rocks in solid black.

2. *Högbrothögdi, Storegut, Mjölkedalstind and Upper Skogadalen.* Although continuity of succession cannot be completely demonstrated throughout this large zone, there is no evidence of major dislocation within it. Minor steep belts, mentioned above, have been mapped between Högbrothögdi and Storegut, and some complexity is developed around the ultramafic body forming a promontory in store Mjölkedalsvatn south of Storegut. In the main, however, the succession seems to be regular.

On Högbrothögdi is exposed one of the most continuous and accessible sections of the layered sequence. To the south the strata are cut off along a sharp down-flexure, the rocks to the south of this being in a state of retrograde metamorphism to be described below. Northwards, in Högbrothögdi, the beds form a gentle arch, followed by a syncline, plunging to the north-east at 20–30°. This is followed northwards by another anticline with its axis along övre Mjölkedalen. The beds from Högbrothögdi may be followed down its northern spur to link across the saddle between Högbrothögdi and Mjölkedalstind with the beds in Storegut, and with those in the south ridge of Mjölkedalstind and the corrie to the east of this.

A continuous succession of north-north-east-dipping strata may be traced along the line of the Eidsbugarden–Olavsbu track, up övre Mjölkedalen, over the saddle (where there are signs of strong rolling out of the rocks, but no loss of conformity) past Sjogholsvatn, and over the south-east flank of Mjölkedalstind to the slopes of Rauddalen.

The beds in övre Mjölkedalen may also be traced over Storegut summit, with northerly dips, swinging slightly west of north in the slopes of Skogadalen north of övre Mjölkedalsvatn.

3. *Other areas of layered rocks.* From a study of aerial photographs it can be seen that sequences of stratified rocks occur in Fleskedalsnosi, Uradalen, and Uranosi, west of the area mapped, and in Storutladalen and Gravdalstind to the north. In these places the rocks are differentiated in such a way as to produce traceable topographic features and they form a suitable region for extension of the present method of mapping.

### *The undifferentiated gneissic jotunites*

The topographic featuring that makes the recognition of layering possible in the areas just described is not developed in all parts of the jotunite region. In Rauddalen, on the northern edge of the map-area, a change takes place in the character of the gneisses to a less well differentiated condition. In this area such ledges as are traceable for any distance may be apparently unrelated to the foliation of the rock that builds them. Layered variations in mineral proportions are not found, whilst planar and linear mineral arrangement is variable and may be somewhat obscure. In general the rocks tend to be mesotype, rather coarse-grained, two-pyroxene feldspar gneisses, and there is an absence of highly feldspathic types. Ultramafic bodies continue to occur, and represent the principal differentiated rock type.

Undifferentiated gneisses of this type are widespread in Jotunheimen, and this no doubt accounts for the delayed recognition of the stratiform character of the massif. Mapping of the ultramafic layers in other parts of the region (e.g. near Spiterstulen) indicates their conformity with the mineral foliation in the enclosing gneisses, and with such layering as is shown, and suggests that the complex is stratiform, even in areas where layering in the feldspathic gneisses is poorly shown. It is to be expected that continued study will enable the structure to be mapped in the absence of visible layering and featuring.

The two-pyroxene feldspar gneisses belonging to the undifferentiated group may, perhaps, be tentatively considered the 'average rock' of the complex, in the sense of Wager and Deer (1939).

While the relationship of the undifferentiated group to the layered group north of Upper Skogadalen and Mjölkedalstind is not exactly known, the passage from one to the other appears to be transitional, and there is no evidence of a major structural break between them.

*Petrography of the jotunites*

Fig. 5 gives Goldschmidt's summary of the mineral composition of the rocks in terms of three species. By using a double tetrahedron (fig. 6) we may introduce olivine, separate the two types of pyroxene, and so

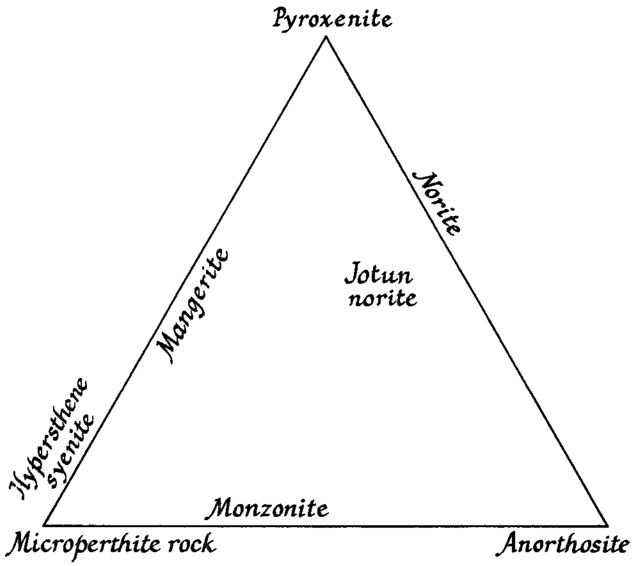


FIG. 5. Mineral composition of Jotun rocks, after Goldschmidt, 1916.

express virtually the whole range of composition of the rocks. In this figure the ultramafic rocks of the complex lie in the face olivine–clinopyroxene–orthopyroxene. No rocks have been observed that would lie in the volume between this plane and plagioclase. That is, there are no representatives with the mineral composition of olivine gabbro or olivine norite. As soon as feldspar enters, olivine disappears, and the rocks fall in the plane clinopyroxene–orthopyroxene–plagioclase or in the volume between this and mesoperthitic feldspar. This reflects the metamorphism that the complex has undergone, during which the reaction

olivine + anorthite = orthopyroxene + clinopyroxene (+ spinel)

has taken place. Green spinel ($n$ 1·780; $a$ 8·132 Å) is concentrated in a narrow zone along contacts between feldspathic gneisses and ultramafics in some cases, in the usual 'coronite' relationship with orthopyroxene (towards the olivine-bearing rock) and clinopyroxene and amphibole (towards the feldspathic rock).

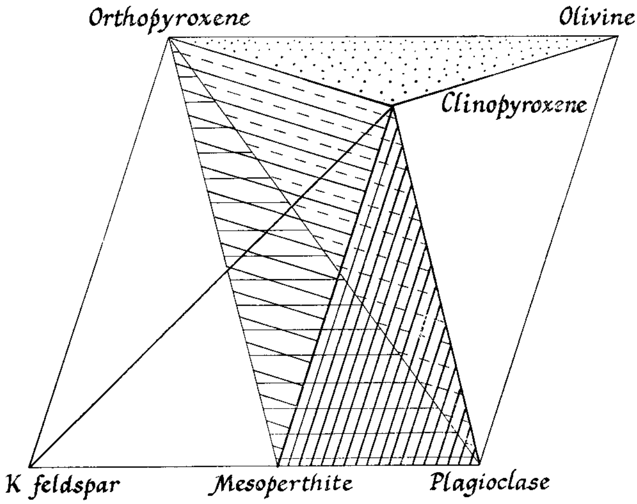


FIG. 6. Double tetrahedron showing mineral composition of Jotun rocks.

The feldspar-bearing rocks forming the greater part of the Layered Sequence show a small scale mineralogical foliation of pyroxenic and feldspathic laminae, parallel to the major layering, and frequently a mineral lineation lying in the plane of the foliation.

In thin section the pyroxenes lie in discontinuous trains of spindle-shaped aggregates in which clinopyroxene and orthopyroxene are involved together. The orthopyroxene tends to invest the clinopyroxene grains, but this relationship is not always shown. Iron ore is always associated with the pyroxene groups. The feldspathic foliae vary in character. There may in different cases be plagioclase alone; plagioclase with a varying proportion of independent amoeboid crystals of potassium feldspar; perthitic and antiperthitic intergrowths of intermediate plagioclase and potassium feldspar; development of porphyroblastic perthite crystals with sub-equal amounts of the two components (mesoperthite of Michot) in a finer-grained matrix of independent plagioclase and potassium feldspar; or the whole of the feldspar may be mesoperthite.

Cataclastic effects are widespread in the jotunites.

In the rocks of the ultramafic group there is not, as far as is known, much variation in the ratio Mg/Fe in the constituent minerals. With the *incoming* of feldspar and the disappearance of olivine, we enter upon a series in which progressive diminution in the amount of pyroxene is associated with an increase in the proportion of potassium feldspar to plagioclase. As the amount of potassium feldspar increases the tenor of anorthite in the plagioclase declines. Ultimately, in a few strata, quartz enters. Magnetite and apatite are important accessory minerals throughout; but zircon, which is rare, is present only in the more feldspathic rocks. These changes suggest the operation of fractional crystallization.

The general trends of chemical composition through this series, towards concomitant increase in $SiO_2$, increase in total alkalis, increasing $K_2O/Na_2O$, fall in CaO, MgO, and FeO, and increasing FeO/MgO have been known since the work of Goldschmidt (1916). The recognition of layered structure in part of the Jotunheim massif provides a basis, hitherto lacking, for further systematic investigation. The study of variation in the mineralogy and chemistry of selected sequences is at present in progress. It is hoped that this will in turn, throw additional light on the structure (see above).

At the present stage, one of the principal problems would seem to be the repetition of sequences, and especially of ultramafic masses, at various levels. Analogy with major stratiform igneous bodies elsewhere would lead us to expect a basal ultramafic layer passing continuously upward (in a broad way) to the most siliceous and feldspathic rocks at the top. In the Jotunheim there are numerous separate pods of ultramafic rocks apparently scattered throughout the succession, though undoubtedly they are more abundant in some zones than in others.

In the region at present mapped there is a concentration of ultramafic layers to the west, where they show continuity over rather long distances, culminating in the belt more than 15 km long from the east side of Kvitevatn to the mouth of Rauddalen and beyond. In a general way, it seems that much more feldspathic rocks lie to the east of this zone.

### *The zone of retrograde metamorphism*

North of the Tyin–Gjende Fault, more especially in the eastern part of the map area, a strip of rocks that have been affected by low-grade metamorphic changes, including alkali feldspathization and epidotization, intervenes between the fault and the stratified succession farther north. In this zone the differentiation that permits mapping of the

Layered Sequence is obliterated. It is noticeable that this zone of alteration is wider to the east where the rocks of the Layered Sequence are more feldspathic in character and presumably more easily modified.

The retrograde metamorphism is ascribed to movements, and access of metasomatizing fluids associated with the movement, on the fault. Similar mineralogical changes have been noted on late faults of smaller magnitude elsewhere in Jotunheimen, for example in the rear wall of the cirque at Gjuvvatn (Battey, 1960*b*, p. 8).

The existence of late, flat-lying faults that bend the foliation, displace ultramafic layers, and are filled with quartz-feldspar vein material in Visdalen, Mid Jotunheimen, has already been referred to. Associated with these movements is the transformation of the jotunite close to the faults into a dark amphibolite sometimes with abundant epidote. The character of this retrogressive metamorphism is different from that along the Tyin–Gjende Fault. It is much more localized, the changes in the jotunites being limited to a few tens of centimetres from the movement planes, while the feldspar introduced forms sheets along these planes, and does not permeate the rocks. The product is usually an amphibolite, which suggests a higher facies of metamorphism than that along the Tyin–Gjende Fault.

## *Conclusions*

1. The two original igneous formations in the area, the Mjölkedola Purple Gabbro and the gneissic jotunites, appear to have had different histories. The former retains igneous textures, while the latter have been fully recrystallized in the granulite facies.

2. The Mjölkedola Gabbro is less differentiated than the jotunites.

3. The jotunites are highly differentiated and have, in part, a stratiform structure and a range of variation in mineral proportions that is most readily explained by igneous sedimentation. The full implications of this hypothesis, as regards repetition of sequences, and mineral composition changes, remain to be worked out.

4. The jotunites have suffered folding and faulting, but they have not been generally metamorphically retrograded during this stage. The time relation of the folding to the metamorphism is not yet established, but there is much cataclasis in some of the rocks.

5. Two types of retrograde changes have affected the jotunites. One is localized along planes of movement well within the boundary thrust of the Jotunheim massif, and produces chiefly amphibolites with associated pegmatitic sheets. The other is associated with boundary faulting

that affects the Mjölkedola Purple Gabbro as well as the jotunites, and leads to mylonitization of the former and general feldspathization and epidotization of the latter.

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*References*

Battey (M. H.), 1960*a*. Rept. XXI Internat. Geol. Congr., Pt. XIII, p. 198.
—— 1960*b*. Norwegian Cirque Glaciers: Roy. Geogr. Soc. Res. Ser., No. 4, p. 5.
Carstens (C. W.), 1920. Norske Geol. Tidsskrift, vol. 5, p. 43.
Dietrichson (B.), 1958. Norges Geol. Undersök. No. 203, p. 5.
Goldschmidt (V. M.), 1916. Videnskaps. Skrifter, Oslo. I. Mat-naturv. Kl., No. 2.
Hödal (J.), 1945. Norske Geol. Tidsskrift, vol. 24, p. 129.

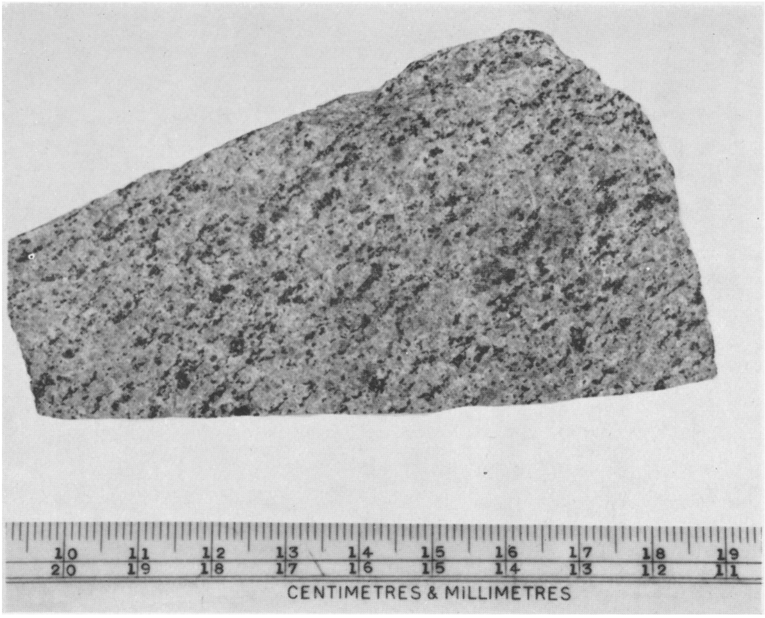
Explanation to Plates

Plate III

Fig. 1. Typical jotunite from south-east slope of Mjölkedalstind.
Fig. 2. Strongly compressed jotunite from Trollsteinkvölven, north-east of Glittertind.

Plate IV

Fig. 1. Small scale layering of two pyroxenes and feldspar, south-west of Glitterheim.
Fig. 2. Mineralogical layering, south slope of Högbrothögdi.

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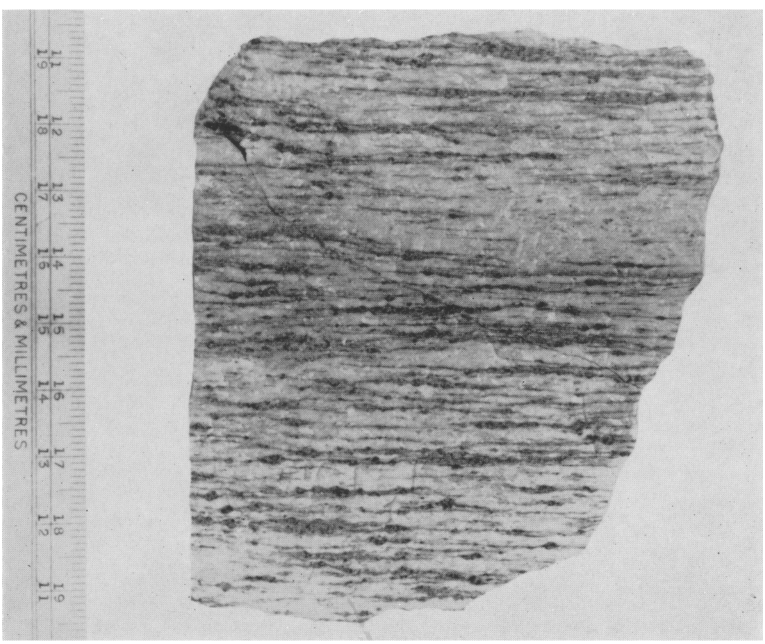


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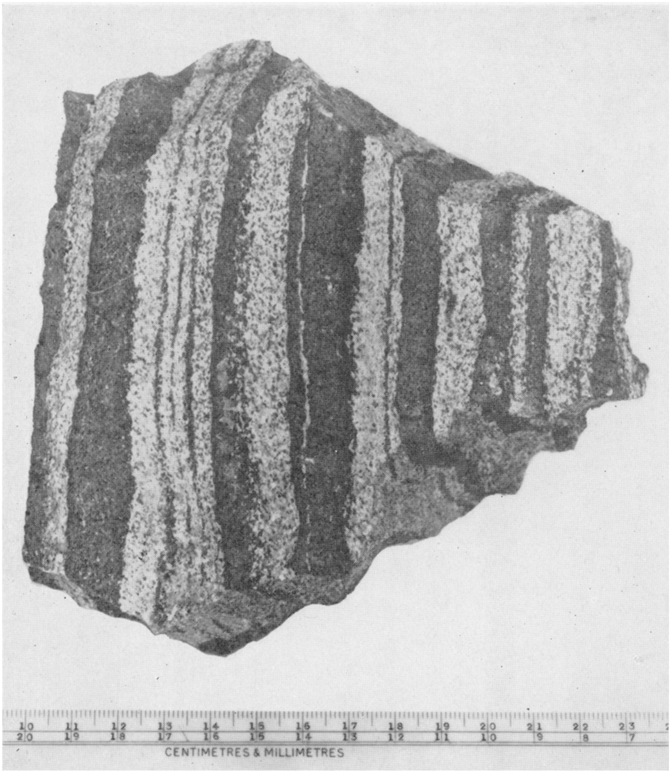
M. H. BATTEY: LAYERED STRUCTURES IN THE JOTUNHEIM COMPLEX

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