On kink-zone development and metamorphic differentiation in the low-grade schists of Norwegian Sulitjelma

by

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Abstract

The common minor scale kink-zones of upper levels of the Furulund schists of eastern Norwegian Sulitjelma generally do not occur in conjugate pairs; usually only the member with northwest dipping axial plane is developed although at lower levels rarely both conjugate pairs and single members occur. The kink zones fit the simple shear mechanism of development proposed by Dewey and Roberts. The upper kink-zones are characterised by a well-developed metamorphic differentiation structure resulting from the juxtaposition of zones alternately rich in mica and quartz. In many of the kink-zones the mica-rich zones are bent by smaller scale folds unknown elsewhere in the region but which are geometrically conjugate to the minor-scale structure in which they lie. Although they clearly are later than the kink-zones it is judged that they are directly related to them.

Introduction

The structures with which this account is concerned are developed in the structurally higher levels of the low-grade quartz-mica schists of the eastern edge of the central metamorphic core of the Scandinavian Caledonides at Norwegian Sulitjelma. The rocks of the area of kink-zone and metamorphic differentiation development (generally east of Lomivann, Fig. 1) are of two main lithologies, black quartz-muscovite phyllites (some homogeneous and some with well-developed thin semi-pelitic layers) and volcanic-chloritic rocks with much marble (Vogt, 1927; Nicholson, 1966). Differentiation is most marked in folds of distinct kink-zone style, the differentiation layering along the kink-zone sometimes being so well-developed that at first sight it resembles bedding.

Development of kink-zones and differentiation structure

1. Most of the kink-zones described here have northwest dipping axial planes (Fig. 7) and axes plunging east of north (regional dips of bedding and

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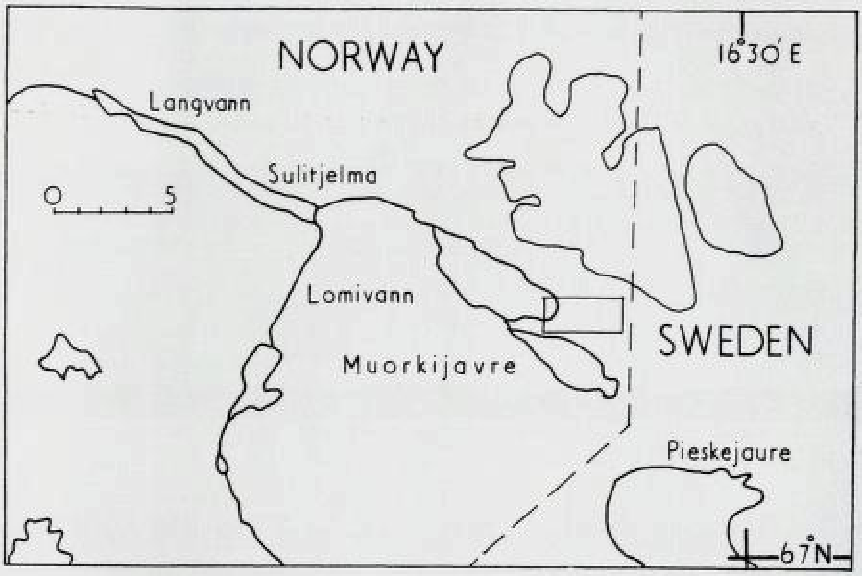

Fig. 1. Outline map of the Sulitjelma region; inset rectangle east of Lomivann limits area in which observations were made. Scale in kms.

schistosity are northerly). At other levels than that at the east end of Lomivann the other member of the conjugate set sometimes is developed on its own and occasionally both members are present. Here we are concerned with a level just below the amphibolites of Sulitjelma (Vogt, 1927, Kautsky, 1953) some 10 km long in which only the northwest dipping minor scale member is present. From west to east at this level there is a gradual decrease in metamorphic grade (Vogt, 1927); the most angular kink-zones are developed in the low-grade rocks to the east while to the west end of Lomivann the apparent equivalents are of somewhat different style but basically the same geometry but without angular hinges. Such folds are associated with one another in what in the field were described as stacked folds in which half a dozen or so folds of the same size and sense of overturn occur together. No conjugate arrangements at all are known in the west.

The sharply angular style of the eastern kink-zones developed in the finely schistose rocks of the east Lomivann area is replaced by a rounder style where more thickly constructed layers are reached and a kink-zone may die out against a thick sequence of such rocks while being able to grow through a bed a few centrimetres thick.

As is common with kink-zones (Paterson and Weiss, 1966, 352) the margin

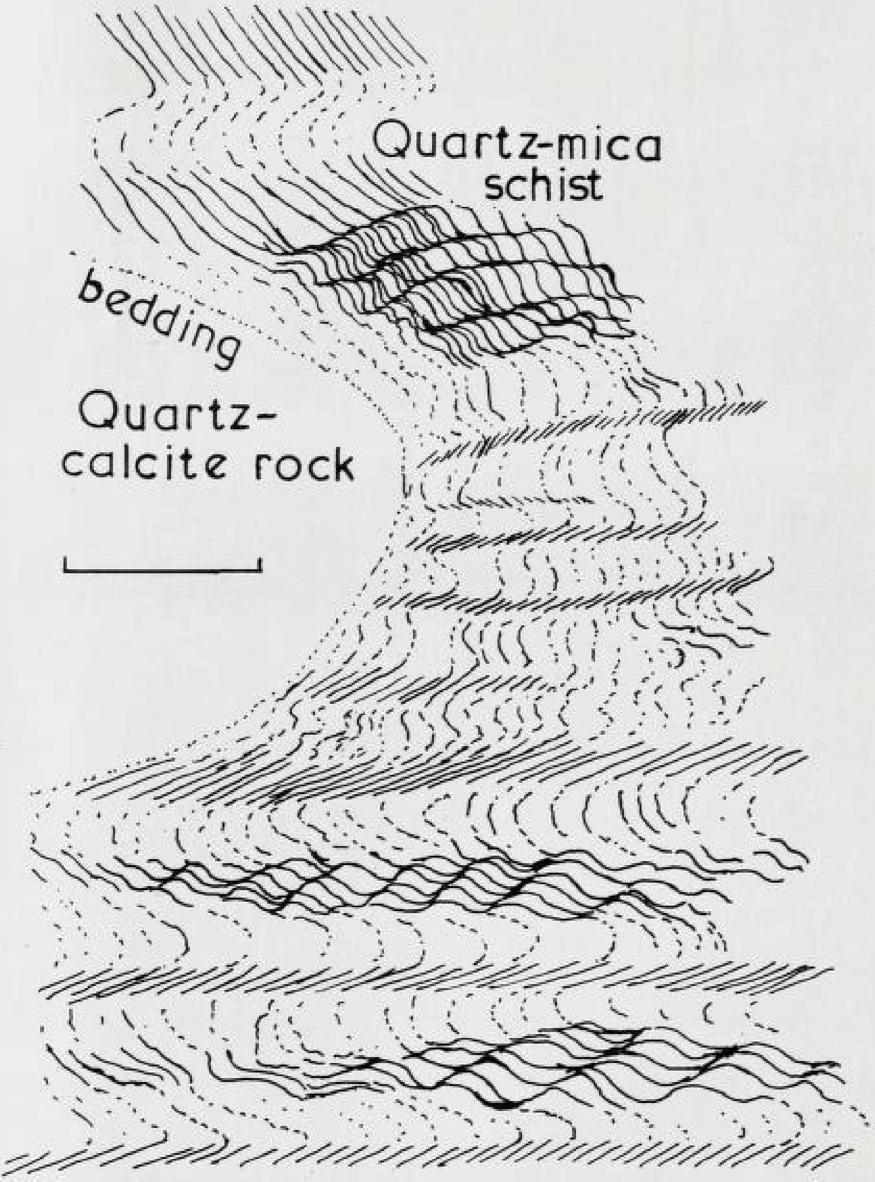

Fig. 2. Sketch of thin section of east Lomivann black phyllite with marked metamorphic differentiation; later folding of suitably oriented micaceous laminae. A part of the area of this sketch is shown in fig. 1. Scale mark 1.0 mm.

Fig. 3. Black phyllite of fig. 2 showing detail of differentiation structure and its folding. Scale mark 0.5 mm.

about bisects the angle between bedding and schistosity inside and outside the kink-zone (bedding and schistosity are about parallel in this region and equivalent to the primary composite banding of Roberts, 1966, 833). The kink-zones often lie at about 30° to 40° to this primary banding and generally are no more than 10 cm. thick. On favourable outcrops the kink-zones can be seen to be little more than 2 to 3 m square, throughout being characterised by continuity of the inherited structure through the kink-zone.

2. As described below the kink-zones often have a finely layered appearance that on close examination is seen to result from the presence of mica-rich and mica-poor layers developed across the primary banding and parallel to the kink-zone margin. Figs. 2, 3, 4 and 5 show examples of the layered structure present in the kink-zones of Norwegian Sulitjelma. The sequence of repeating elements of the structure, quartz-rich and mica-rich layers, may be 20-30 cm thick, the thickness of the kink-zone itself. The layered structure is found only in the finely foliated (or schistose) semi-pelitic rocks, stopping as massively chloritic or psammitic and more broadly bent layers are reached; behaviour which is perfectly understandable when it seen that the two elements of the

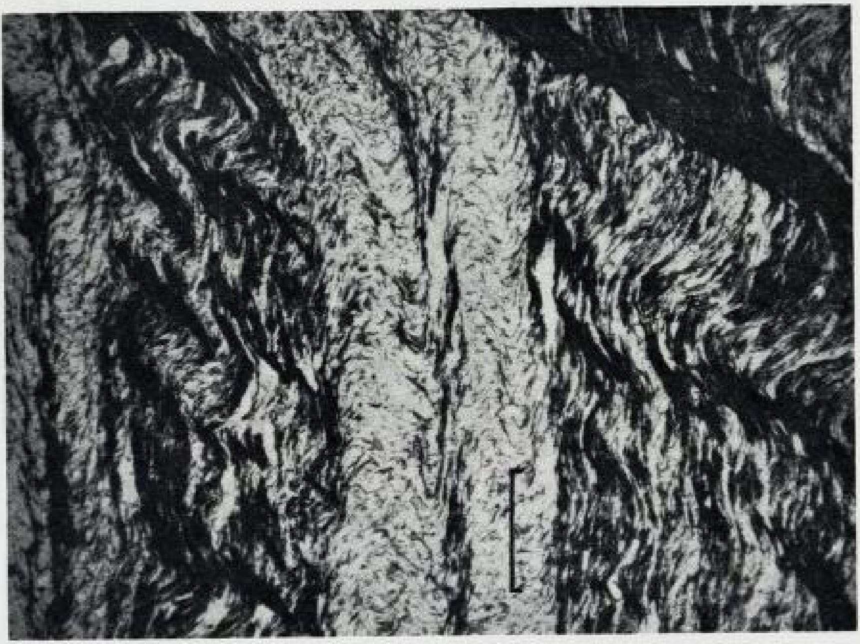

Fig. 4. Quartz-mica differentiation in east Lomivann black phyllite. Folding later than its development; here affecting both quartz-rich as well as mica-rich layers. Scale mark 0.5 mm.

secondary structure are constructed from different parts of the small folds within the kink-zone. Clearly only material which can fold on this small scale can give rise to it. As Figs. 2 to 6 show the Sulitjelma kink-zones are yet more complex for the differentiation structure itself is folded.

Fig. 2 of a section normal to the kink-band axis (and to the axes of the larger of the microscopic-scale folds seen in this figure and the photomicrograph of Fig. 3) shows the schistosity of the black phyllites passing through the differentiation layers. Where mica is preponderant, schistosity lies at an acute angle to the layer while in quartz-rich zones schistosity lies more or less normally across the band. This layered differentiation structure was described first by Clough (1897) and its units were called strain bands by him. The short limbs of the Sulitjelma kink-zones are composite therefore, being made of several almost microscopic sets of folds or strain bands through which continuity of fabric is preserved as it is on the larger scale of the kink-zone. Since the layered structure lies along a kink-zone it follows that the limbs of the small folds making up the structure are strictly parallel to neither the long

Fig. 5. Metamorphic differentiation structure in kink-band of black phyllite (trending gently upwards from left to right) and folds of this structure (trending more steeply upwards from right to left).

limb of the kink-zone nor to the average attitude of the short limb, both limbs have been deformed. Also it is clear that the kink-zone margin is not the bisector of the angle between primary banding attitudes inside and outside of the small folds (Fig. 2). In some ways these small folds of about equal limb length are comparable in style with chevron folds, in this case however, unequal thicknesses of the primary banding in different limbs allows the axial plane to be nearer one set of limbs than the other.

3. Figs. 2, 3 and 4, 5 and 6 show not only the differentiation structure typical of Sulitjelma kink-zones but also folds of this structure while Fig. 3 shows the pattern of Fig. 2 over a wider zone of the same rock. The folds of micaceous elements clearly are later than the differentiation structure. They have the same sense of rotation over the whole of the kink-zone (being on that scale of conjugate motion with it), while on the small scale the relationship is of alternately conjugate and non-conjugate motion. The two fold systems are not contemporary of course; all member of one set are earlier than all of the other. Functionally the second set are kink-zones also although they are not tabular but occur only within thin mica-rich zones. Examples of the geometric relations between the two sets are given in Fig. 7 parts 2, 3 and 4. The angle between the minor and microscopic scale developments varies

Fig. 6. Kink-type fold in Lomivann black phyllites with set of crenulations whose axial traces lie along the trace of the minor-scale fold (along direction of pen) and a subsidiary and crossing set (along direction of pencil), restricted to the axial zone of the fold.

considerably from one example to another although most commonly the angle is about 50°, as in Fig. 7, parts 3 and 4, so that the two "kink-zones" are at an acute angle to one another over the presumed maximum principal stress.

Fig. 2 provides an interesting example of the way in which differentiation might upset the orderly development of kink-fold sets for the new planar structure is less easily kinked than the rock from which it formed. Secondly it illustrates the way in which the quartz-poor regions even when strongly folded cannot develop the type of modal variation possible in the initial quartz-mica schist. The pseudo-conjugate structure is developed only in the kink-bands themselves and on the scale described above rather as if it could form only on the transposed schistosity of the kink-bands. In spite of the obvious age difference the writer regards the two fold sets as being almost as closely related as truely conjugate structures.

Genesis of kink-zones and differentiation structure

1. Historically there have been two sources of interest in kink-like structures, firstly the natural occurrences of such structures in rock on a minor fold scale and secondly the development of geometrically similar arrangements in deformed crystals; both enquiries date back into the last century. The most

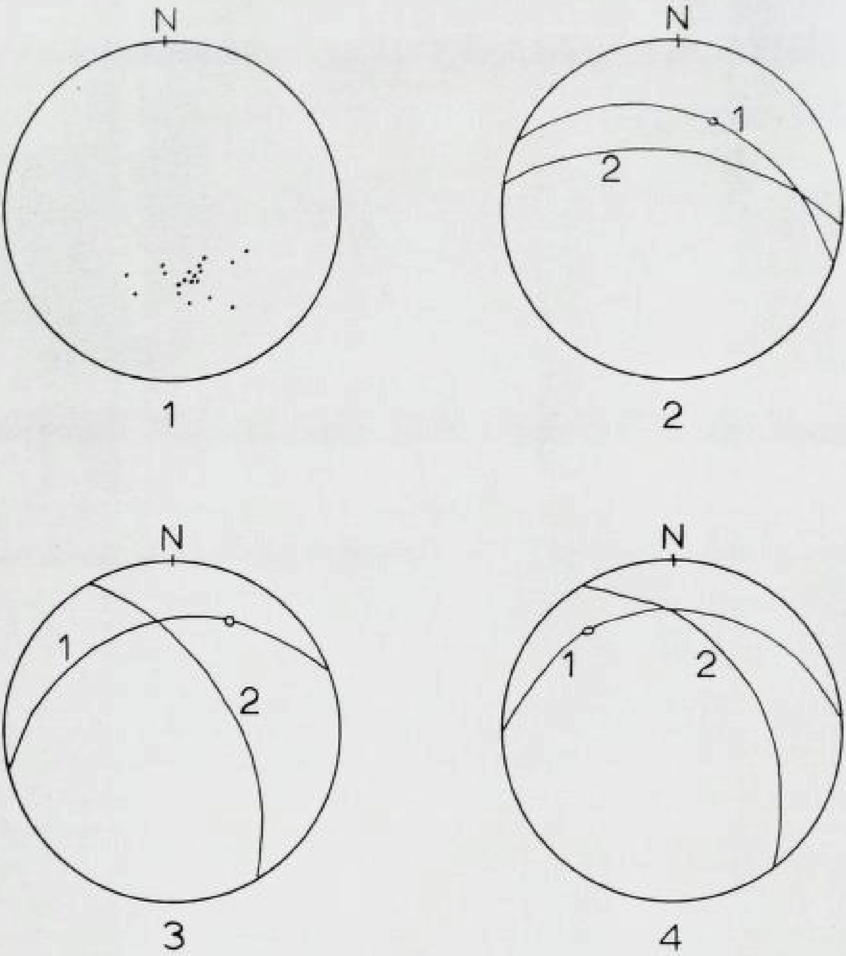

Fig. 7. 1. Poles to kink-zones, east Lomivann. 2, 3 and 4. Traces of crenulation planes for three rock specimens from east Lomivann. 1, main member with circle showing bedding (and schistosity) intersection with crenulation plane (and thus with kink-zone). 2, subsidiary member, developed only in kink-zones of type 1.

recent and most developed investigations of the second sort are those of a group at the University of Calilfornia concerned in the first place with calcite (for example, Turner, Griggs and Heard, 1954); from this study have grown analytic and experimental studies of geometrically similar rock structures (Patterson and Weiss 1962; Heard, Turner and Weiss 1965; Patterson and Weiss 1966). Amongst the latest studies based on the field examination of kink-zones and in both cases using analytical tools developed by Flinn (1962), are accounts by Dewey (1965) and Roberts (1966). As Roberts has very recently pointed out there are substantial differences in the conclusions reached in these two ways for both Dewey and Roberts accept an important class of kink structures produced by simple shear while the Californian school propose that the same class of structures are the products of bend-gliding.

The writer finds the geometric arguments of Dewey and Roberts compelling and thus accepts that some kink-zones are produced by simple shear and that those produced by bend-glide (flexural slip is an alternative name for this mechanism) should have dislocations on the margins; thus continuity of structure through the kink-zone is one piece of evidence in favour of the simple shear mechanism. If this mechanism is accepted then such kink-zones in rock are more comparable to the slip domains of calcite described by Heard, Turner and Weiss (1965), rather than the kink-zones of calcite. Basically the difference of opinion concerns the character of the strain in the marginal planes of kink-zones; all recognise the need for strain there that is compatible with the strain regimes on both sides. Dewey and Roberts point out, however, that it is not enough that such compatibility be present at the end of development of the structure but that it must exist throughout so to preserve the continuity of the earlier developed arrangements to typical of kink-zones. It is on this need that they decide the inadequacy of bend-glide of flexural slip mechanism for structures like those described here from Sulitjelma. At Sulitjelma as for the Dalradian rocks described by Roberts there is an absence of the structure necessary to define the strain in detail. Again like the Dalradian rocks, however, there is an absence also of the contemporary structures which might suggest triaxial strain which therefore is accepted as substantially biaxial.

The simple shear mechanism of kink-zone development does not seem to provide any sufficient reason why the kink-zone margin should commonly bisect the angle between primary banding inside and outside the kink-zone. If this relationship is regarded as common and revealing then this is a deficiency in the theory. Dewey, however, has described folds (for instance 1965, Fig. 17 B) in which the kink-zone margin is far from bisecting the banding angle. Thus it is not absolutely clear that near equality of angle is especially significant although it is reported by Patterson and Weiss as typical of their experimental results (1966, Fig. 6) and certainly occurs in the Lomivann examples. Roberts (1966, 847) clearly supposes that the primary banding of the short limb will not be rotated when it has reached a position normal to the maximum principal stress; on his simple model of kink-zone folds this is achieved when the two angles from the kink-zone margin to the banding on either side are equal. Such an end to rotation seems obvious in the homogeneous strain investigated by Flinn (1962) but not so obvious in zones of simple shear in which the banding supposedly is mechanically passive.

As Roberts suggests (1966, 851) the appearance of only one member of the potential conjugate set might result from a stress field oblique to the composite banding. Kehle (1964, p. 284) has proposed for fractures a slightly different context in which there might be unequal development of the members of a conjugate set, viz. that the local stress field might be symmetric while the far stress field in general might not be so and thus that the work necessary to cause virtual displacement on one member of a conjugate set would be less than that necessary on the other. Both arguments might apply here as the kink structures seen to have formed late in a thrusting episode and the far field stress field then presumably was not symmetrical.

2. It has been suggested that the differentiation structure developed by the diffusion of quartz from highly strained zones followed by precipitation in adjacent less strained ones so that modal variation was produced in a once homogeneous rock (Nicholson, 1966, Roberts, 1966, p. 850). The structures which define the quartz and mica-rich zones clearly are part of the minor-scale kinks and coeval with them. The inner complexity of the kink-zones seems to have been early in development for if the kink-zone long limbs are undeformed during much of kink development and a simple shear mechanism operative (both suggested by Dewey (1965, p. 470-471) and Roberts (1966, p. 841)) then simple shear must be responsible for it too and there is no reason to separate its time of development from that of he kink-zone itself. Since quartz diffusion presumably is a relatively slow process it seems that the kink-zones themselves did not achieve their finished form abruptly. In addition it is easier to suppose that the kink-zone started with its present width rather than grew wider as Paterson and Weiss (1966, p. 367) suggest; in this way all the component zones have the same time for development (clearly they have the same structural character).

There is no evidence at Lomivann for migration of quartz beyond the major kink-zones; quartz veins are not common and those that do occur show no special distribution with respect to them. Since the differentiation structure is always on the same scale and does not occur much magnified in bigger folds it is clear that conditions for its development are suitable only in the small folds, perhaps because both the contrast and degree of strain necessary to produce such quartz migration in schistose quartz - mica fabric only takes place on this scale.

Clough (1897, 22) described the development of differentiation as an example of "... the law that in the thinned limbs quartzose parts of the bands diminish in quantity, while the micaceous remain the same or increase," and Dewey (1956, 475) has already suggested quartz mobility in kink-zones although he did not relate it closely to the development of strain-bands. Although Clough (1897, 20) like Dewey (1965, 486) and Rast (1965, 89), does seem to suppose that some of the mica of the Cowal kink-zones is new (thus supposing mobility of its components) it is clear that the attitude of some of it fits the mica of the pre-strain-band schistosity as in the example of Fig. 2 for Clough writes (1897, 20) that "mica in the slips [strain slips or strain-bands] is not always quite parallel to the sides of the slips, but has a small angle, approximately that at which the earlier banding [and usually schistosity (Clough 1897, 9)] approaches the slips." This description fits the common case described above where there is a continuous mica fabric through moth the mica and quartz-rich zones. Later development as proposed by Roberts (1966, 850) may include the growth of a mica-felt along the kink-zone margin as Dewey (1965, 486) and Rast (1965, 90) have earlier suggested. This stage is not reached at Lomivann.

The usual starting point of discussions of metamorphic differentiation is Eskola (1932) and the development of strain-bands can be conducted in its terms. The formation of alternating mica- and quartz-rich layers in the folded fabric provides examples of Eskola's second and third principles of differentiation within a rock mass (1932, 70), namely the principles of enrichment in the most stable constituent and the solution principle. The "exogenous force" (Eskola 1932, 70) that drives the process is deforming stress. Thus the differentiation phenomenon is a synkinematic one.

It has long been supposed that quartz readily migrates and Eskola (1932, 77) made special reference to such migration. Voll (1960, 556, 557) has described its importance both in general in metamorphic rocks and in particular in the development of mica films on secondary schistosity planes in situations very like that under discussion here. Voll, however, attributes the generation of the fine plications of the schistosity directly to shear planes, the mica films forming on such planes by the solution of quartz and relative enrichment in micas. In the Sulitjelma rocks, however, no clear-cut shears are present for schistosity is continuous through the kink-bands and their internal folds although there is markedly varied strain from layer to layer of the structure.

Conclusions

It is difficult to fit the Lomivann kink-bands into Dewey's classification of kink structures although those parts of kink-bands which pass through less closely foliated rock are close in geometry to this fourth group, that of smoothly curving similar folds. However, most of the kink-bands are present in black phyllites and are slab-sided with foliation continuous through them; thus they are superficially similar to Dewey's third group (1965, 485) although lacking the felt of mica along the kink-boundaries that he described as characteristic of this group. It is the writer's view that Dewey is wrong in putting Clough's strain bands in this third group where indeed he makes them the type examples. Although their geometry is close to that of the fourth group of Dewey the writer regards Clough's examples as of the same origin as those of Lomivann, that is, essentially simple shear kink-folds.

Clough's structures perhaps have more similarity with ordinary crenulation cleavage than with kink-bands and their presence here widens the discussion to include the development of differentiation in crenulation or strain-slip cleavage, a matter given general consideration by Roberts (1966, 848). The writer has already suggested a close similarity (Nicholson, 1966) for as Turner and Weiss (1964, 465 and 487) have said crenulation cleavage is characterised by "periodically spaced thin domains of intense strain" while "the intervening laminae (the microlithons of De Sitter) show evidence of pronounced internal strain in the form of crenulated relic S foliation". It seems that in general these crenulation folds are simple shear structures as Roberts has described (1966, 848) sometimes modified by SiO_2-diffusion and metamorphic differentiation.

The metamorphic differentiation of the Sulitjelma rocks is a synkinematic phenomenon involving the solution of quartz in, and its diffusion from, zones of high strain and its precipitation in adjacent less strained zones, mica remaining passive, the folds controlling its regular development being crenulations of an earlier schistosity. Such crenulations and the differentiation structure may occur within clear kink-band structures or within minor scale folds of other style. In all cases there is a clear relationship between fold size and style and the nature of the lithological sequence. When developed in bigger folds the structure parallels the axial surface of the larger fold.

Since kink-bands are best developed in thinly foliated rocks the bands and the related differentiation structure are characteristic products of late deformation phases in schistose rocks. Except for mica and quartz the mineralogy of the earlier rock is not relevant. For example at Ntungamo in Uganda (Nicholson, 1965) good differentiation occurs in staurolite schists (Fig. 1, Nicholson, 1966) while at Sulitjelma and Cowal it occurs in much lower grade rocks. It is clear that the development of differentiation will inhibit or strongly modify kink-zone evolution so that it may be only in mica-rich rocks that the climax of the conjugate relation, the development of folds affecting all the rock will be reached (Paterson and Weiss, 1966, 367, Fig. 17, Roberts, 1966).

McNamara (1965), has proposed that the development of quartz segregations (not all of kink-band type) in the lower-grade schists of Cowal has a broad P-T control as segregations do not occur in the lowest grade of the region. He also proposes (1965, 374) that the marked differences in amount of quartz segregation between occurrences in massive greywacke and mica schists is attributable "to the increased amount of solution of quartz in the more sheared rock, because abnormally high surface energies on portions of the detrital quartz grains, due to stress, cause the silica to dissolve more readily, leading to supersaturation of the pore fluid; on relaxation of the stress, the quartz is redeposited". To fit the petrographic evidence of strain bands it is necessary to modify McNamara's hypothesis to allow synkinematic precipitation in a less strained zone.

References

Clough, C. T., 1897. In Geology of Cowal by Gunn, W., C. T. Clough and J. B. Hill, Mem. Geol. Surv., Scotland.

Dewey, J. F., 1965. Nature and origin of kink-bands. Tectonophys, 1, 459-494.

Eskola, P., 1932. On the principles of metamorphic differentiation. Bull. Comm. Géo' Finlande, 16, 68.

Flinn, D., 1962. On folding during three-dimensional progressive deformation. Quart. J. Geol. Soc. Lond., 118, 385-433.

Heard, H. C., F. J. Turner and *L. E. Weiss*, 1965. Studies of heterogeneous strain in experimentally deformed calcite, marble and phyllite. Univ. of Calif. Publ. in Geol. Sci., 46, 81-152.

Keble, R. O., 1964. Deformation of the Ross Ice Shelf, Antarctica. Geol. Soc. Amer Bull., 75, 259-286.

McNamara, M., 1965. The lower greenschist facies in the Scottish Highlands. Geol. Fören. Forh. Stockh., 87, 347-389.

Nicholson, R., 1965. The structure and metamorphism of the mantling Karagwe - Ankolean sediments of the Ntungamo gneiss dome and their time-relation to the development of the dome. Quart. J. Geol. Soc. Lond., 121, 143-162.

— 1966. Metamorphic differentiation in crenulated schists. Nature, 209, 68-69.

— 1966. On the relations between volcanic and other rocks in the fossiliferous east Lomivann areas of Norwegian Sulitjelma. Norges Geol. Unders. 242, 143-156.

Paterson, M. S., and *L. E. Weiss*, 1962. Experimental folding in rocks. Nature, 195, 1046-1048.

Paterson, M. S. and *L. E. Weiss*, 1966. Experimental deformation and folding in phyllite. Bull. Geol. Soc. Amer., 77, 343-374.

Rast, N., 1965. Nucleation and growth of metamorphic minerals, Controls of Metamorphism, ed. Pitcher W. S. and G. Flinn. 78-102.

Roberts, J. L., 1966. The formation of similar folds by inhomogeneous plastic strain, with reference to the fourth phase of deformation affecting the Dalradian rocks in the southwest Highlands of Scotland. J. of Geol., 74, 831-855.

Vogt, Th., 1927. Sulitelmafeltets Geologi og Petrografi. Norges Geol. Unders., Nr. 121.

Voll, G., 1960. New work on petrofabrics. L. pool. Man Geol. J., 2, 503-567.

Turner, F. J., D. T. Griggs and *H. C. Heard*, 1954. Experimental deformation of calcite crystals. Geol. Soc. Amer. Bull., 65, 883-934.