Eidsvoll Quarry, Oppdal, South Norway: A One-Outcrop Model for some Aspects of Trollheimen–Dovrefjell Tectonics

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Complex small-scale folds in feldspathic psammite and metadolerite at the 'Eidsvoll' flagstone quarry near Oppdal accurately represent many of the large-scale Caledonian structures of the mountain areas Trollheimen and Dovrefjell. The quarry rocks are heterogeneously deformed. They display cross-bedding, isoclinal recumbent folding, tectonic thinning, tectonic repetition or interlayering, transposition of layering by tight recumbent folding, interference fold patterns producing tubular folds, and other structural geologic features observed at regional scales about three orders of magnitude larger. The quarry is near the main Oslo–Trondheim highway (E6), and can serve as a one-stop excursion, illustrating aspects of the geology of the whole region.

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Introduction

Within the intensely deformed and metamorphosed Western Gneiss Region, the areas of Trollheimen and Dovrefjell are relatively little disturbed and well understood. Holtedahl (1938) recognized mappable Caledonian rock units and recumbent folding here long ago, and Hansen (1971) found that the styles and areal distributions of the folds themselves were mappable. New rock correlations and interpretations of the avaiable mapping indicated a surprisingly clear regional tectonostratigraphy (Krill 1980, 1985). However, in most of the Western Gneiss Region farther to the west, and indeed, within some parts of Trollheimen and Dovrefjell, the deformation is so complex and the stratigraphy so disturbed that the reliability of the interpretations may easily be doubted. Demonstrations of the stratigraphical continuity and the large-scale structural features of Trollheimen and Dovrefjell require an extensive field excursion, including visits to rather remote areas (Krill & Roshoff 1981). However, one remarkable set in folds in 'Eidsvoll' flagstone quarry along highway E6 depicts, in a single outcrop, many of the regional stratigraphic and structural patterns. These folds are presented here as an example of the structural style, and as a focus for discussion of some of the stratigraphic, structural, and *Stockwerk*-tectonic interpretations.

Geologic setting

Descriptions and interpretations of the stratigraphy and structure of Trollheimen and Dovrefjell are available elsewhere (Hansen 1971, Gee 1980, Krill 1980, 1985). The Precambrian gneissic basement (Lønset gneisses, etc.) is unconformably overlain by a sparagmite-like psammitic cover (Åmotsdal unit, Fig. 1). Although basal conglomerate is recognized locally (Fig. 2) the basement and cover generally appear fully concordant, and even interlayered or transitional. Four to five far travelled Caledonian nappes form the overlying tectonostratigraphy. The lowermost, Risberget Nappe includes augen gneiss and rapakivi granite (Krill 1983a), metagabbro and meta-anorthosite, and various other Precambrian crystalline rocks. The Sætra Nappe consists of sparagmite-like psammite with Late Precambrian dolerite dikes (Krill 1983b). The Blåhø and Surna Nappes include strongly metamorphosed marine sediments and volcanites, apparently of Late Precambrian to Ordovician age. The uppermost, Tronget–Støren Nappe contains the weakly metamorphosed marine sediments and volcanic rocks of the Trondheim Region.

Following the emplacement of the lower nappes and during the emplacement of the Tronget–Støren Nappe, all the rocks were metamorphosed, recumbently folded and refolded. Some recumbent folds apparently involved only the base-

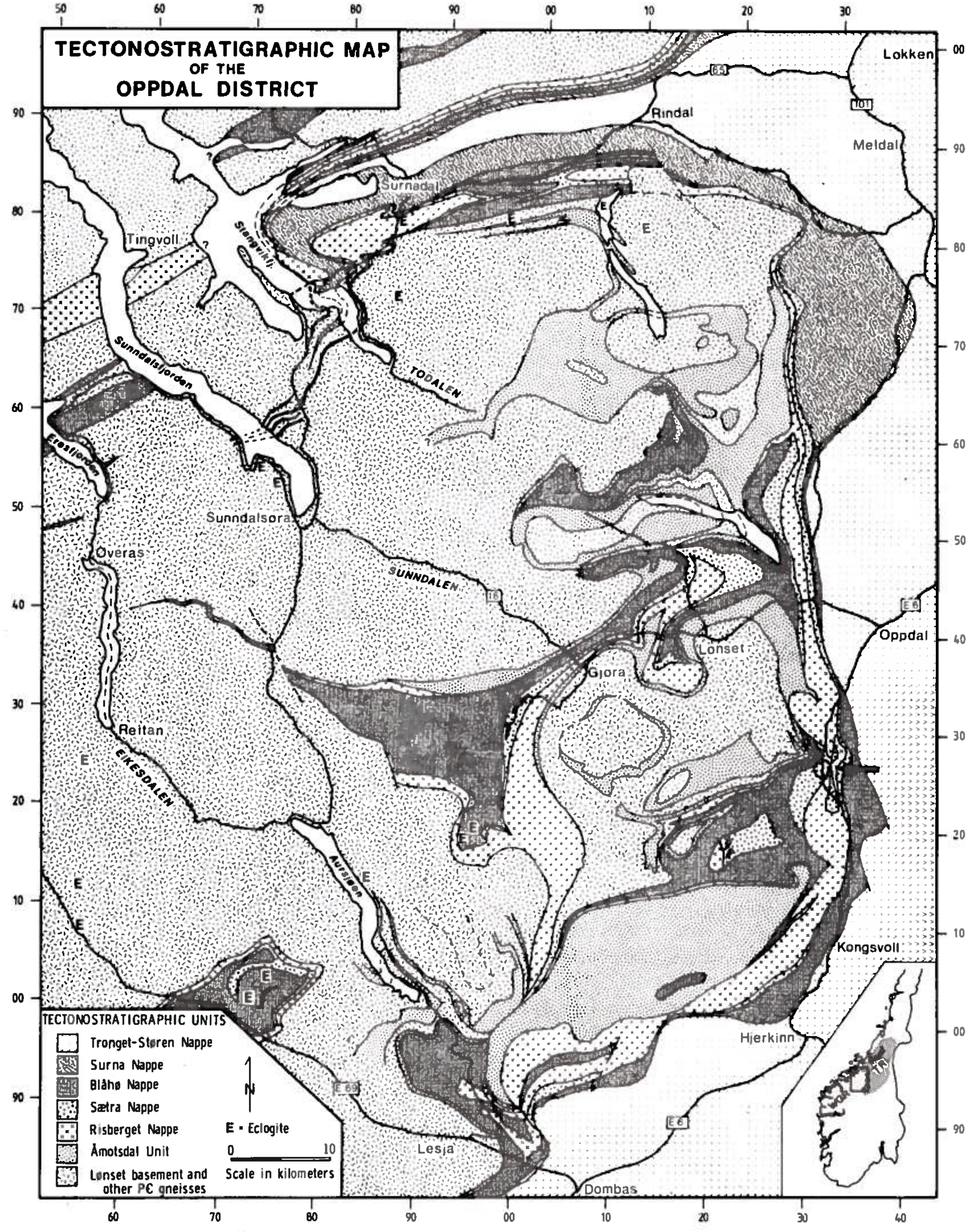


Fig. 1. Tectonostratigraphic map of the Oppdal district of Trollheimen and Dovrefjell. Margin index indicates UTM coordinates. The six-digit coordinates in the text refer to the E–W and N–S coordinates: Eidsvoll quarry (circled) has coordinates 299256.

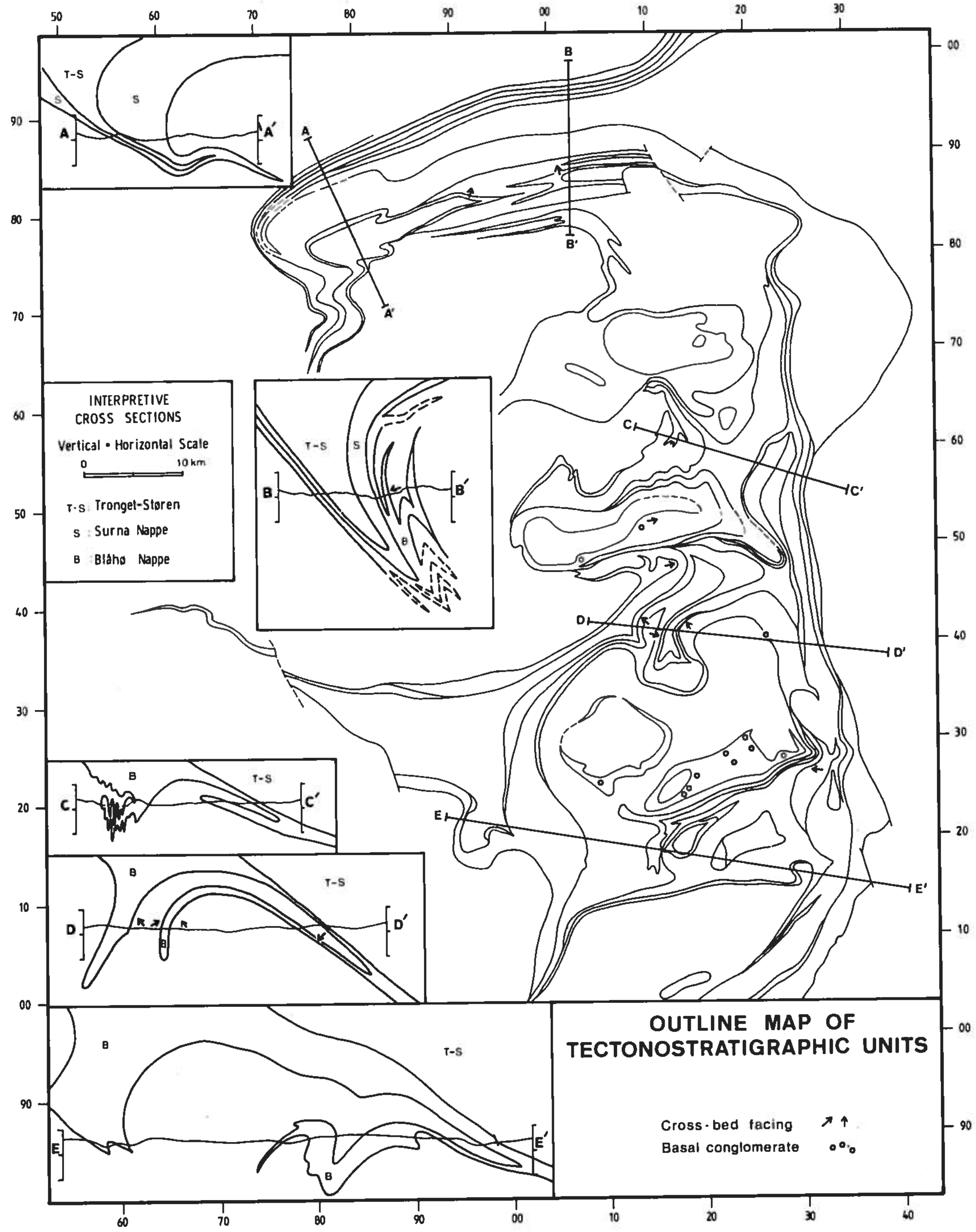


Fig. 2. Outline map and interpretive cross-sections.

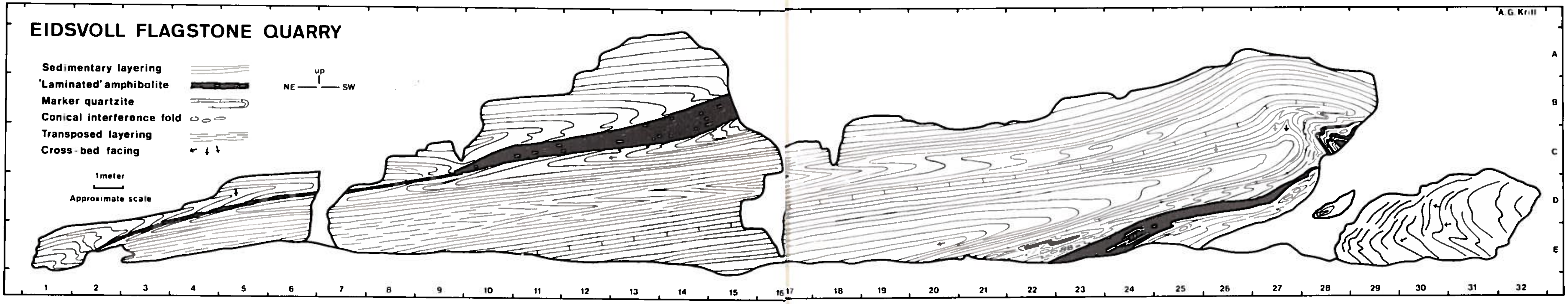


Fig. 4. Simplified drawing of Eidsvoll quarry outcrop with letters and numbers along margins for reference. Rock surface is nearly vertical but azimuthal orientations vary: 045° from positions 1E to 25B,C,D,E; and 027° from positions 25B,C,D,E to 29B. Isolated parts of outcrop are shown in plane of drawing as projected parallel to fold axis and lineation directions, which plunge 12–19° towards 065–092°. Note that outcrop surface is not perpendicular to fold axes, so apparent tightness of folding is somewhat exaggerated.

ment and Åmotsdal units, while others included all the rocks below the Tronget–Støren Nappe. One large recumbent fold also deformed the Tronget–Støren Nappe. The structural patterns resemble the *Stockwerk*-tectonic model of Wegmann (Hansen 1971, Krill 1985) with structural detachment of recumbently folded rocks (infrastructure) beneath a relatively weakly deformed overburden (superstructure).

Fig. 3. Quarryman cracking flagstone slab along scored line.

Eidsvoll quarry

The outcrop of folded flagstone of the present study is located at 'Eidsvoll quarry', UTM grid coordinate 299256, on the 1:50,000 map-sheet Snøhetta 1519 IV. The quarry (Fig. 1) is about 16 km south of Oppdal, east of highway E6, but not visible from the highway. The quarry exploits the well foliated psammite of the Sætra Nappe. The psammitic flagstones of this quarry are some of the 'flaggiest' of those quarried in the Oppdal district. Skilled quarrymen, using only a hammer and chisel, can split large blocks of psammite into flagstone slabs over 100 cm in diameter and less than 1 cm thick. The slabs are then scored and broken like panes of glass (Fig. 3).

The folded rocks of main interest here are not within the quarried area, but are at the entrance to the quarry (Fig. 4). The proximity of a dolerite dike apparently induced structural heterogeneities allowing folding and irregular deformation of the psammite. The folded rocks have no value as flagstone and have not been quarried.

Cross-bedding

The least deformed psammite is found at the southwest end of the outcrop (Fig. 4, 29E–32D), where cross-bedding is well preserved (Fig. 5). Cross-bedding faces north as shown schematically by arrows on Fig. 4. At the northeastern end of the outcrop (2E), cross-bedding is more disturbed by folding and by small, sub-horizontal faults, but the facing direction is clear. Most other cross-bedding shown in the drawing is very strongly sheared and much less clear. It is best seen when the rock is wet.

The cross-bedding is selectively preserved in the hinges of some folds, where the sedimentary layering is least sheared. (Note that the cross-bedding at 29E–32D is in the hinge of a poorly exposed northward-facing fold). Where cross-bedding is preserved in a fold hinge, the fold may be considered to be an 'F_1' structure – the first penetrative deformation affecting that part of the rock. A similar relationship is seen for the Holberget fold, the best-defined large-scale recumbent fold in the Trollheimen–Dovrefjell area. Abundant cross-bedding is well preserved in the anticlinal core of the large Holberget recumbent fold (Fig. 2, UTM coordinates 120390, cross-section D–D') supporting other evidence that this fold is an 'F_1' structure. Other well preserved cross-bedding to the north (140420, Fig. 2) may indicate the remains of another F_1 closure, but further detailed mapping and structural study will be necessary to interpret the multiple folding there.

Cross-bedding recognized in the Eidsvoll outcrop faces downward and northward. On the upward-facing limbs of the folds, any original cross-bedding has been sheared beyond recognition and no upward-facing cross-bedding is found. On the regional scale, cross-bedding is also surprisingly consistent. Cross-bedding in the psammites of the Sætra Nappe both here in the quarry area and south of the Surnadal synform (020860, and 930830, Fig. 2) consistently faces away from the tectonostratigraphically underlying Risberget Nappe. The cross-bedding at Eidsvoll quarry and in nearby roadcuts of highway E6 is inverted, as the entire Sætra Nappe is inverted here on the lower limb of the large-scale Holberget recumbent fold. Where cross-bedding is seen in the Åmotsdal psammites it consistently faces upward, away from the underlying basement gneiss domes.

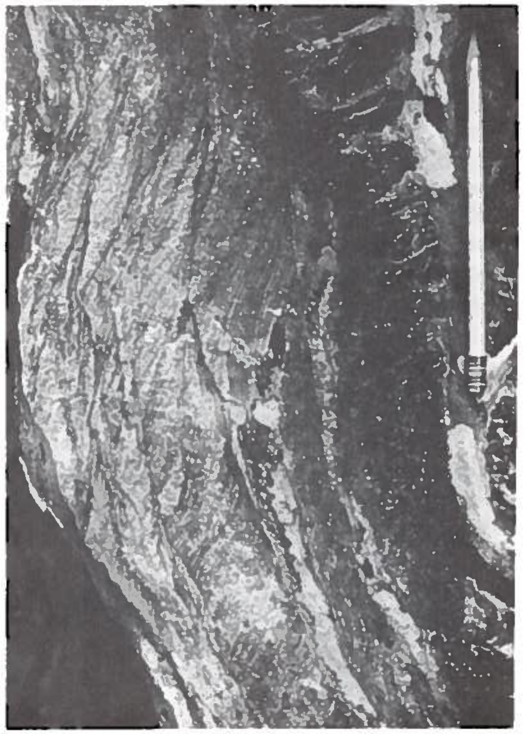


Fig. 5. Cross-bedding in psammites (position 30E on Fig. 4).

Fig. 6. Folds above and below strongly deformed dike (position 6D on Fig. 4). The dike did not intrude parallel to the axial planes of pre-existing folds, but rather, the folds formed adjacent to the cross-cutting dike. The geometry corresponds to the central part of Fig. 7c, and to the pattern of recumbent folding beneath the rocks of the Trondheim Region.

Recumbent folding

The dominant structure of the Eidsvoll outcrop is a southward-closing recumbent fold, with axial surface exposed from 19E to 29B. This structure repeats many of the stratigraphic layers seen in the outcrop, just as the large-scale recumbent folding commonly repeats the tectonostratigraphic units in Trollheimen and Dovrefjell. A pink quartzite layer in the Eidsvoll outcrop is about the most external layer that can be followed continuously around the recumbent fold. As marked on Fig. 4, it is traced from 11E along the upper limb, around the hinge of the fold at 28B, and along the lower limb to 21E. It averages 100–200 mm thick along the upper limb, but is only 1–10 mm thick along the lower limb. All the layers thin dramatically along the lower limb, and many completely disappear in places. (Note that in Fig. 4 the thinning of the sedimentary layers is not well represented by the spacing of drawn lines, as it was necessary to terminate some closely spaced lines that represent extremely thinned layers. The average thinning along the lower limb is better estimated by comparing the vertical distance between the axial surface of the fold and the position of the marked quartzite in the upper and lower limbs.)

In recumbently folded rocks, thinning is commonly observed in the lower limbs of antiforms and the upper limbs of synforms. The general facing directions of cross-bedding clearly indicate that this main fold is a syncline, but the thinning along the lower limb suggests that it is an antiform. In fact it is both an antiform and a syncline, as the entire tectonostratigraphy is inverted here. To further complicate matters, the Holberget recumbent anticline is synformal here (Fig. 2). Thus, the Eidsvoll fold could be formally designated a 'small-scale antiformal recumbent syncline on the lower limb of a large-scale synformal recumbent anticline.

The important point here for comparison with the large-scale structures is that extreme thinning is a natural result of tight folding. Such thinning is clearly demonstrated by the large-scale map pattern (Fig. 1) but it is difficult to evaluate which units were thinned by the folding, and which were thinned through pinch-and-swell deformation during and subsequent to nappe emplacement. However, in mapping these strongly deformed rocks, even very thin units should be noted, to enable accurate interpretation of the stratigraphy and structure.

Metadolerite dike

The metadolerite dike at the Eidsvoll outcrop is penetratively foliated and transformed to biotite–amphibolite, a process involving some schemical exchange between dolerite and psammite (Krill 1983b). Tight folds occur both above and below the foliated dike (Fig. 6). The numerous dikes in the quarry area display various degrees of deformation, and observations suggest that the folds form by simple shear with rotation adjacent to an originally cross-cutting dike. A schematic drawing (Fig. 7) shows the presumed development. Gayer et al. (1978) have described the geometry of such folds and discussed the presumed mechanism of folding.

In the Eidsvoll outcrop, the marked quartzite layer helps to define the position of the amphibolite layers. The amphibolites are in the same approximate position on the outside of the quartzite layer in the recumbent antiform. Although the dike was presumably cross-cutting, it is now nearly reoriented parallel to the general psammite layering. It has been tectonically transformed into a pseudo-stratigraphic unit – a 'tectonotratigraphic' unit. A large-scale analogy is the Risberget Nappe. The Risberget rocks were originally part of a Proterozoic gneiss terrane, and now, following the extensive thrusting and folding, the Risberget Nappe is a superficially concordant Caledonian tectonostratigraphic unit.

Ductility contrast

The metadolerites of the Sætra Nappe demonstrate rather curious properties of structural competence. In early stages of deformation the dike rock is much more competent than the psammite. The dikes act as rigid ribs, and the psammite is both shielded from early stages of shearing and folded against the dikes. With further deformation the dikes become extended and form boudins, becoming strongly foliated amphibolite. Eventually, as in the Eidsvoll outcrop, the metadolerite is transformed into a thinly laminated amphibolite, which is no more competent than the psammite and is plastically deformed in the same ductile style. On the large scale, rocks of the Risberget Nappe appear to demonstrate a similar variation in structural competence. Large bodies of augen gneiss and gabbro of the Risberget Nappe form competent megaboudins (280310, 190160, 150350), and adjacent rocks are plastically folded, or thinned and cut out along the megaboudin margins. Elsewhere, similar Risberget rocks become extremely thin and ductile, deforming coherently with other rock units. The rocks of the Risberget Nappe and the Sætra dolerites were originally relatively dry igneous rocks, which were deformed together with hydrous metasediments. The change from competent to ductile deformation of the Risberget rocks and the dikes is presumably related to penetration of fluids during folding and metamorphism.

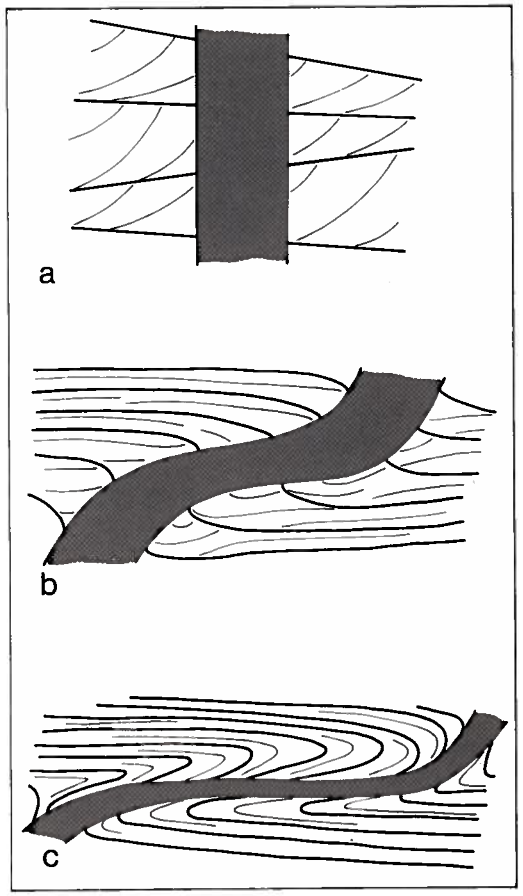


Fig. 7. Schematic drawing of development of isoclinal folds adjacent to dolerite dike.

Fold interference patterns

In addition to the main folding, the amphibolite is strongly foliated and laminated with thin lenses of psammite that were apparently folded together with it during the extreme deformation. Some of the thin psammite lenses form detached isoclinal fold hinges. Such complex interlayering of rock types also occurs on a larger scale in Trollheimen and Dovrefjell, but where it is limited to local rock contacts it is not shown in Fig. 1.

Some layers are thicker and therefore mappable. The amphibolite lens at 22,23E (Fig. 4) illustrates how rocks can become interlayered by superposition of two intense phases of folding. Deformed sedimentary layering in the psammite wraps completely around boths ends of the lens, showing that isolation of the lens was produced by a fold interference pattern; the lens is not a small thrust slice or an original sill or apophysis of the dike. On the larger scale, the lens of Sætra rock in the Risberget Nappe just east of here

(306260 Fig. 1) has a recumbent-fold termination on its northern end. This lens was formed either as an interference fold pattern, or an isolated fold hinge. The origins of other large-scale lenses shown in Fig. 1 are less clear, as they might have formed during either the original thrusting or the tight folding.

In the Eidsvoll outcrop, the interference pattern of the amphibolite lens as well as conical folds in the strongly deformed psammite (22,23E, 25D, 27D, 28D and 28C) clearly demonstrate the presence of two phases of isoclinal folding. Hansen (1971) demonstrated methods of analyzing such fold patterns in Trollheimen. The regular positioning of the conical folds at 22,23E suggests that they are dome-and-basin interference patterns (Type 1, Ramsay 1962). The slip line, or orientation of relative rock motion, during development of the second of the two interfering folds can theoretically be determined from such interference patterns. However, the psammite here is mica-poor and the order of formation of the interfering folds cannot be determined from mica orientations. Furthermore, the conical folds are so tight that they are tubular in shape and, despite a few centimeters relief in one fold, it was not possible to distinguish basins from domes.

In general, the second slip line in such interference folds is limited by the angle of divergence of the walls of the conical fold, so that it must be about parallel to the axis of these tubular folds. The axis plunges 14° toward 065° at position 22,23E and 12° toward 068° at 28D. These orientations must approximate the slip line of the second fold phase. The nearly parallel orientation of slip lines, fold axes, and stretching lineations strongly suggests that the deformation resulted from convergent flow of the rock. Such parallel orientation of lineations is common in the cores of salt domes and in parts of Trollheimen (Hansen 1971), where convergent-flow environments are inferred for the formation of large-scale interference folds (140600, Fig. 1).

Transposition

In the Eidsvoll outcrop, a later set of folds, with vergence opposite to that of the F_1 folds, initiates disharmonically at 24,25C. The folds become tighter, with sharper hinges to the north and by 9D,E the original sedimentary layering is completely transposed. Within the transposed zone, individual sedimentary layers cannot be traced beyond a few meters, whereas elsewhere in the outcrop sedimentary layers are continuous for tens of meters. If such transposition of layering had occurred between two contrasting rock-types, the result would have been a complex interlayering of the rocks parallel to the strong foliation. The development of such transposition is very difficult to demonstrate on the large scale because it requires nearly perfect exposure and very detailed mapping. However, it seems likely that much of the complex interlayering between distinctive rocks such as augen gneiss, psammite, and metavolcanites in many parts of the Western Gneiss Region is the result of transposition during tight folding.

In the Eidsvoll outcrop, continuous, unfolded sedimentary layers are found both above and below the folded and transposed layering. The layers did not act as completely passive markers during the deformation, but must have retained some strength parallel to the layering in order to guide the folding and transposition between unfolded layers. The geometry of such large-amplitude, tight, recumbent folds requires that the folded rocks be confined between layers not involved in the fold. This point is important in interpretation of timing of thrusting and large-scale recumbent folding in the Trollheimen – Dovrefjell region.

Although some tectonostratigraphic units are not involved in some of the recumbent folds, it cannot be assumed that thrusting of those units occurred after the folds had formed.

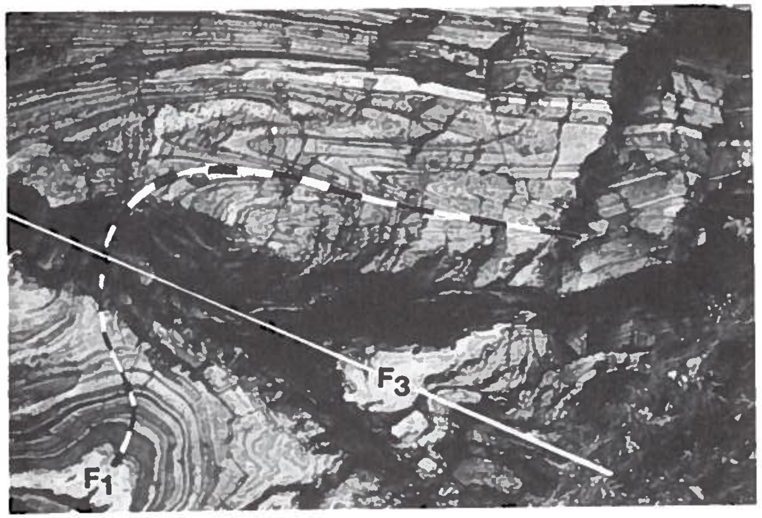
The initiation of the set of similar folds at 24,25C is a 'root zone' of the fold and of the transposition. The layers involved in the fold appear to detach from the adjacent layers below (25,26C). On the large scale, the Holberget recumbent fold has a very similar root zone; from the map pattern (110379, Fig. 1) the psammites of the Åmotsdal unit appear to detach abruptly from the underlying Lønset basement gneiss.

Recognition of fold phases

Recognition of the various phases of folding in the Eidsvoll outcrop is difficult, because the fold axes are nearly parallel, the axial planar foliations are only weakly developed, and the folds vary dramatically in style. The main recumbent syncline with axial plane from 19E to 27C is an isoclinal F_1 fold. Only the hinge of the complementary F_1 anticline is exposed in the isolated part of the outcrop at 29D, 32D. Here the fold style is more open, and the cross-bedding is much better preserved.

The conical interference patterns (Fig. 4) indicate a second phase of isoclinal folding (F_2). A later antiform (F_3, Fig. 8) with an axial plane trace from 27B to 29C folds both the F_1–F_2 interference patterns and the axial plane of the main F_1 syncline. The F_3 fold becomes relatively open where it crosses the axial plane of the F_1 syncline, but then develops into the tight fold producing transposition as previously described. Thus the tightest fold observed in the outcrop is an F_3 fold.

Fig. 8. F_1 folds refolded by F_3 fold (position 27,28B,C on Fig. 4). Traces of axial planes of F_3 fold and one F_1 fold are shown.



As in the Eidsvoll outcrop, small-scale folds are nearly coaxial in most parts of Trollheimen and Dovrefjell. Multiple phases of small-scale folding are found at some locations, while rocks at other locations were never folded or foliated. Both the use of fold-style criteria to designate fold phases and the designation and correlation of the phases (e.g. F_1, F_2 . . .) must be applied very cautiously here. Only a very tight 'F_n' fold can usually be recognized after refolding by an 'F_{n+1}' fold, because any open 'F_n' folds would be obliterated. But the tight 'F_n' folds presumably form by progressive folding of open folds, so that in an area of heterogeneous deformation with subparallel fold axes, a weakly developed 'F_n' fold will generally appear similar to an 'F_{n+1}' fold, and distinction of fold phases of the basis of style criteria is not secure.

Stockwerk-tectonics

One of the oldest and most intriguing tectonic interpretations of Trollheimen and Dovrefjell is the *Stockwerk*-tectonic model of Wegmann (1935, 1959). According to that model, the western Gneiss Region was an infrastructure that developed through Caledonian granitization beneath the superstructure of the Trondheim Region. A zone of shear and detachment, called the *Abscherungszone* formed between the infrastructure and superstructure.

Most of the original model has been discredited. The 'infrastructure' consists mainly of Precambrian gneiss, not granitized Caledonian rocks, and the *'Abscherungszone'* is a thrust surface with considerable displacement. The term *Stockwerk*-tectonics has been retained nevertheless, to emphasize that a ductile infrastructure was apparently active beneath a detached superstructure. The Eidsvoll outcrop demonstrates how tight recumbent folds might have developed in a relatively ductile rock against a more competent rock, especially if the contact was originally discordant. Small-scale recumbent folds formed consistently against the dike. Despite extensive deformation, the original discordance is generally preserved. Only where the dike is most strongly folded into the psammite, as in the interference folds, is the discordance no longer visible. Similar relationships of recumbent folds and discordance against metadolerite dikes are seen elsewhere in the quarry area.

On the regional scale, large recumbent folds are common in the rocks of the Western Gneiss Region below the rocks of the Trondheim Region (Tronget–Støren Nappe, Fig. 2). A structural discordance can be recognized nearly everywhere beneath the Tronget–Støren Nappe, even at the far western end of the Surnadal synform (720780). However, as demonstrated by small-scale fold relationships between the psammite and the dikes, such structures do not show that the rocks of the Tronget–Støren Nappe were thrust into position only after the recumbent folding.

Regional metamorphic studies indicate significant differences in temperature and pressure between the Tronget–Støren Nappe and the underlying infrastructure (Krill 1985). Thus at least part of the discordance is clearly a relatively late thrust fault, but the positioning of the recumbent folds below the discordance suggests that it represents a relatively early zone of structural detachment as well.

It is not known if rocks from the Tronget–Støren Nappe are involved in the large interference folds of Trollheimen and Dovrefjell. These folds contain rocks of the Blåhø Nappe in their synformal cores, and the Blåhø rocks are very similar to the overlying Tronget–Støren rocktypes. If the lithological contrast between Blåhø and Tronget–Støren rocks were greater, such as the contrast between the metadolerite and psammite of the Eidsvoll outcrop, this uncertainty would not exist.

Conclusion

Interpretation of the Eidsvoll quarry outcrop is relatively straightforward in comparison with interpretation of the large region of Trollheimen and Dovrefjell. The quarry outcrop is nearly perfectly exposed, completely mapped, and shows no significant metamorphic- or sedimentary-facies changes. Nevertheless, the outcrop demonstrates many regional geologic features, even some details of the *Stockwerk*-tectonic development; and it thus can serve as an introduction and guide to the tectonics of Trollheimen and Dovrefjell.

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