Fabrics and structure of metamorphic flagstones and implications for industrial quality

TOM HELDAL & BJØRN LUND

Heldal, T. & Lund, B. 2000: Fabrics and structure of metamorphic flagstones and implications for industrial quality. *Norges geologiske undersøkelse Bulletin 436*, 137-146.

Metamorphic flagstones are characterised by a regularly spaced mica foliation separated by quartzo-feldspathic domains, along which the rocks can be cleaved into commercial slabs. In the thrust nappes of the Scandinavian Caledonides, such deposits are essentially developed from psammitic rocks in high-strain zones. Recent investigations have shown that the industrial quality of many flagstone deposits can be linked to several aspects of the tectonometamorphic development of the rocks, and especially to rapid vertical and lateral variations in strain. Field relations and microtextures from three different flagstone deposits are described and used as examples. Finally, a structural and textural characterisation of flagstones is proposed.

Tom Heldal and Bjørn Lund, Norges geologiske undersøkelse, N-7491 Trondheim, Norway.

Introduction

For many centuries, metamorphic flagstone[1] has been an important, traditional construction material in Norway. These rocks are easily cleaved into slabs along mica-rich foliation planes with simple tools, and have, throughout history, found a wide range of applications, such as roofing tiles, paving slabs and blocks. Earlier, flagstone was the poor man's building material, since there were many easily accessible deposits which could be exploited more or less freely. Today, however, flagstone production has become a large-scale industry, using advanced quarrying and processing technology. Norwegian flagstone products, like roofing and flooring tiles and thicker slabs for cladding and paving, have in recent years reached a gradually expanding market in Scandinavia, Central and Southern Europe and the Far East.

As the stone industry grows and evolves from traditional, small-scale operations towards larger scale, the need for geological information on the quality of deposits and future reserves is increasing. This leads us to an important question: which geological features are important in controlling the quality of the flagstone, and how can we establish a methodical approach regarding our understanding of these types of deposits? In this paper, we will focus on one important aspect regarding flagstone quality, namely, the mechanisms behind the formation of flagstone cleavage, and how an understanding of these mechanisms can help us in obtaining a better prediction of flagstone quality and investigation of deposits. Field relations and microstructures from three different flagstone deposits (Alta, Oppdal and Dovre; Fig. 1) will be used to resolve these questions.

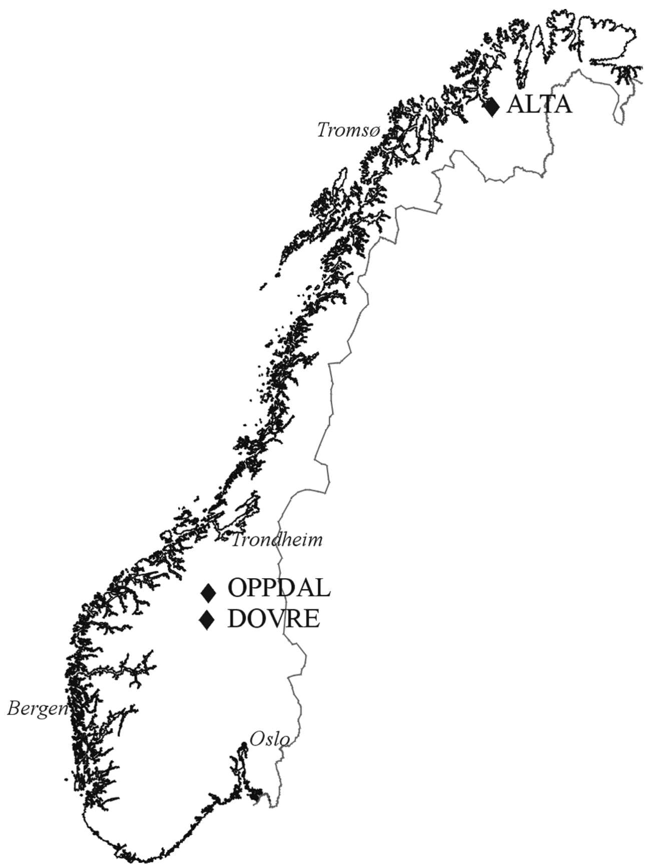


Fig. 1. Location of the Alta, Dovre and Oppdal flagstone deposits.

1. Our use of the term 'flagstone' needs some explanation. In Norwegian, the term 'skifer' is used for all rocks which contain a closely spaced lepidoblastic foliation. Commercial 'skifer' can be physically cleaved into slabs along the foliation. For rocks with clearly defined quartzofeldspathic domains between the mica-layers, the prefix 'kvarts-' is used. Some companies use the name commercial 'quartzite' for these rocks, in order to distinguish them from 'softer' slate in the market, even if, in geological terminology, they cannot be classified as such. In English, the term 'flagstone' generally applies for non-metamorphic, thin-bedded sandstones. However, we have chosen the term 'metamorphic flagstone' to be the most suitable for their metamorphic equivalents with a pronounced, spaced schistosity, to avoid confusion with slate and schist.

What is a commercial flagstone?

A commercial flagstone deposit has a well defined, spaced, mica foliation, along which the rock can be easily cleaved. The most continuous and obvious mica layers are planar and parallel, and the spacing between them equals the average thickness of commercial slabs, usually between 1 and 3 cm (Fig. 2). Between the mica layers are domains consisting mainly of quartz and feldspars. Thus, slabs are essentially quartzo-feldspathic in composition, coated with a thin film of micas.

The quality of flagstone deposits depends on a series of features. Firstly, it relates to the need for easy cleavable slabs of suitable size and thickness, depending on the end-product in question. Furthermore, the slabs must be planar, have uniform surfaces and thicknesses, and show no surface staining or other features which could influence the customer's impression of the final products. To maintain a profitable operation, quarry waste must be reduced to a minimum. Consequently, the spacing of joints and veins should be as wide as possible, folds should be absent or only sporadically present in a quarry site, and the geometry of the deposit should give easy access to sufficient reserves without necessitating the removal of too much waste rock.

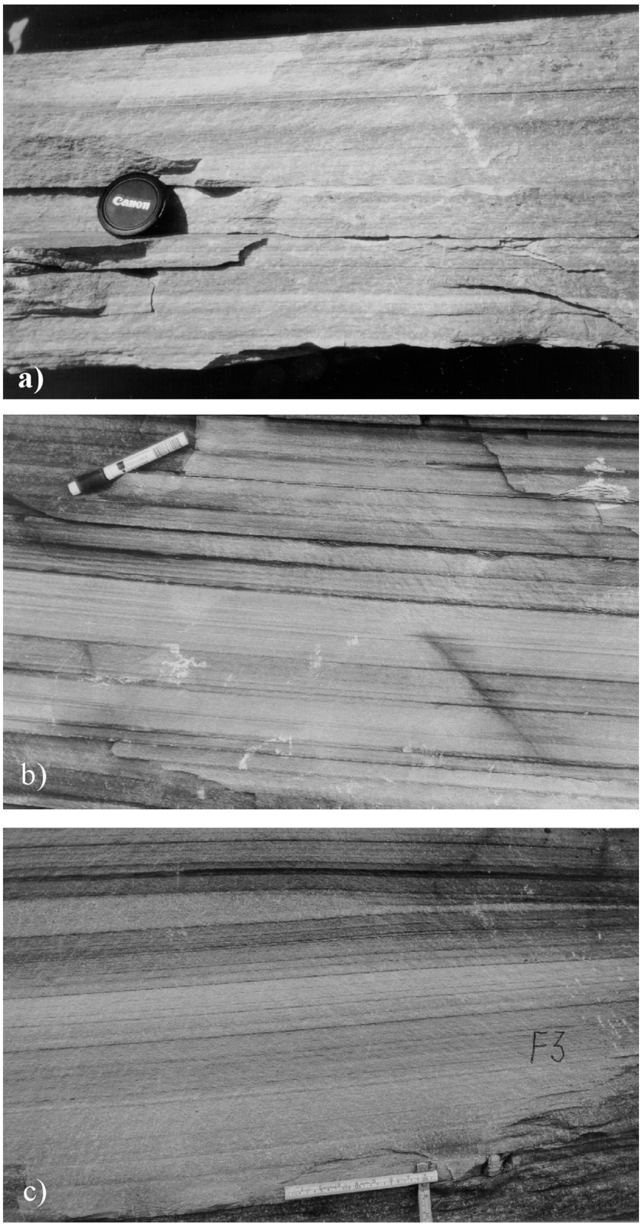


Fig. 2. Photographs of typical flagstone sections at (a) Oppdal, (b) Dovre and (c) Alta. Note wider spacing of cleavage and more diffuse cleavage planes in (a) than in (b) and (c).

Even though the three flagstones in question have approximately the same appearance, i.e. grey with a micaceous schistosity surface, there are important differences which are appreciated by and well known to quarrymen and users. The Alta flagstones are known to be extremely hard and durable and are produced as thin slabs. At the other end of the scale, the Oppdal flagstones generally have a wider spaced schistosity, are easier to work with and are more porous. The Dovre flagstones fall somewhere in between the other two, though are closer to the Alta than the Oppdal flagstone. The major differences in average technical properties are summarised in Table 1.

These differences are also reflected in the production of the three types. The Alta flagstones are widely used as roofing tiles and thin tiles for flooring. This type is considered to be expensive to cut with disc saws and to polish. The Oppdal flagstones are hardly ever used for roofing, as the slabs tend to be to thick and heavy, and absorb more water. On the other hand, Oppdal flagstones are considered to be excellent for thick slabs for paving and building blocks. An important method for formatting and shaping slabs is splitting perpendicular to the cleavage, which is easily done with simple tools. This is actually not possible to achieve in the case of the Alta flagstones.

	Alta	**Dovre**	**Oppdal**
Average slab thickness	10-20 mm	10-25 mm	15-40 mm
Sawing properties	extremely hard	hard	soft
Colour on polished surface	dark grey to black	dark grey	light grey
Ability to split across foliation	difficult	difficult	excellent
Water absorption	extremely low	low	medium
Bending strength	high	high	medium

Table 1. Some properties for the Alta, Dovre and Oppdal flagstones.

Structural evolution

Although we cannot recall any papers dealing specifically with the geology of metamorphic flagstones, many unpublished reports and fieldwork over many years by NGU geologists have consistently suggested that workable flagstone deposits develop from psammites (arkose or sandstone with a pelitic component) in high-strain zones characterised by strong flattening and thinning of original layers. Typically, metamorphic grade has reached middle to upper greenschist facies. The Norwegian flagstone deposits may, in fact, be uniformly associated with thrusts, sheared contact zones or the highly strained long limbs of major folds. The three flagstone deposits in question occur within Caledonian thrust nappes in different parts of the country.

As this article highlights the mechanism of deformation as a flagstone-forming process, the timing of deformational events and controversies concerning this will not be discussed here. Furthermore, this is not an attempt to correlate deformation episodes from Alta to Dovre, and the numbering of such deformation episodes below must be regarded only as a tool to emphasise that the psammites at the three localities in question have undergone approximately the same pattern of deformational evolution. From the work of several authors (Zwaan & Roberts 1978, Guezou 1978, Roberts 1985), it seems well established that at least three to four episodes of *Caledonian* deformation can be identified at all three locations. The early, ductile deformation, commonly referred to as D_1 and/or D_2, involved, according to these authors, thrusting, folding and subsequent gravitational flattening, reaching the thermal maxima during the D_2 episode. Zwaan & Roberts (1978) described early D_2 thrusting with the development of blastomylonites followed by a gravitational flattening deformation within the Kalak Nappe. Krill (1980) described a similar development from the Oppdal area, while our own mapping of the Dovre flagstone indicates a D_2 stage of thrusting also in that area (Lund 1979, Heldal & Sturt 1996). As a final result of this early deformation, the strong, penetrative 'flagstone' foliation (Fig. 2) is developed in high-strain zones, such as in the thinned long limbs of folds, along sheared primary contacts and within thrust zones.

The D_2 event was followed by a later stage of semi-ductile to brittle deformation, hereafter referred to as D_3. Principal structures are essentially coaxial with D_2, but occurred at a higher crustal level and at lower metamorphic grade. Structures include small- and large-scale folds with steeper axial planes than the earlier folds, thrusts and steep reverse faults, kink-bands and joints, especially in the areas of fold hinges. In pelitic layers, a crenulation cleavage is commonly developed, especially in fold hinge zones. A later, D_4 event is characterised by normal faults, fracture zones and regional, open folds with steep axial planes.

Thus, the tectonometamorphic evolution involves the generation and shaping of the flagstones during shearing and flattening at approximately the same time as the peak of metamorphism was reached. Subsequent folding and thrusting at lower temperatures within the same stress system and, finally, non-coaxial faulting and folding under even 'colder' conditions affected the flagstones to various degrees. The structures of the early ductile deformation can be regarded as constructive for producing good-quality flagstone deposits, whilst the later structures, where present, combine to destroy the flagstone quality by jointing and fracturing along faults and in fold hinge areas, and by buckling and crenulating of the S_2 flagstone foliation. In the following, we focus on how the variations of important quality aspects within the flagstones, such as cleavability, slab thickness and other physical properties, can be studied in the light of these early, ductile deformational events.

Field relations and microstructures

The Alta flagstone

The *Alta flagstones* occur within the Nalganas Nappe (Zwaan & Gautier 1980), which is a subdivision of the Kalak Nappe Complex within the Middle Allochthon of Finnmark (Roberts 1985, Ramsay et. al. 1985). The Nalganas Nappe consists of a succession of meta-arkoses and mica schists resting upon allochthonous, Precambrian gneisses within the Nålfjell Group (Zwaan & Gautier 1980). The extractable flagstone unit occurs in the central part of the nappe, with non-exploitable meta-arkoses beneath and above in the northern part of the area (Fig. 3). The uppermost part of the nappe comprises mica schists with intercalated psammitic layers.

The workable flagstone unit varies in thickness from 40 to 100 m, and locally grades laterally into schistose psammites with a poorly developed schistosity. The variations in thickness seem to be the result of strain, indicated by a positive

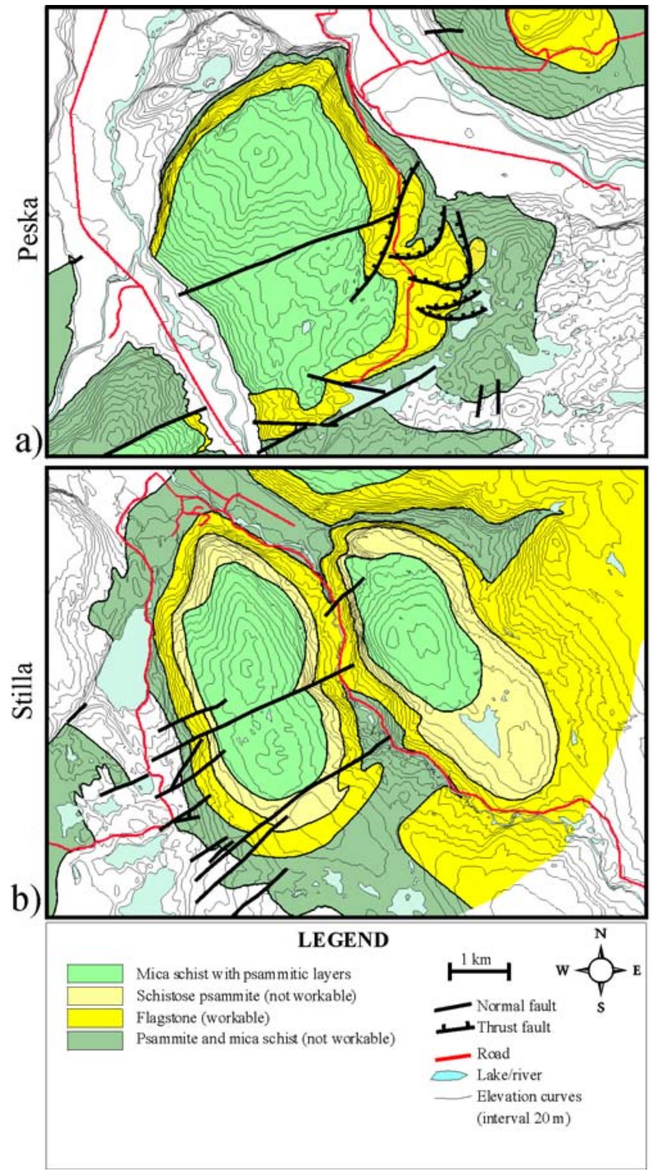
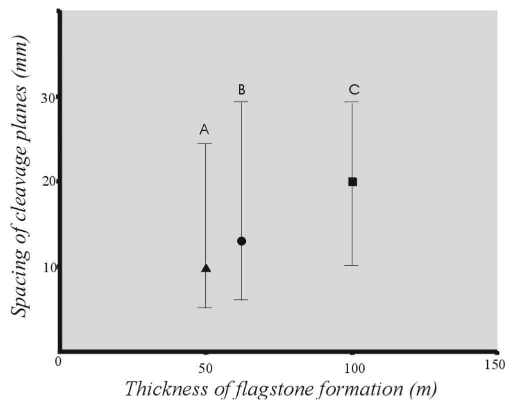


Fig. 3. Geological maps of (a) the Peska-Langvann quarry area and (b) the Stilla area, both within the Alta flagstone deposit (from Heldal et al. 1997).



C

Fig. 4. Average spacing of cleavage (slab thickness) plotted against total thickness of flagstone unit at three different locations within the Alta flagstone deposit. Points equals average spacing and line range of measurements. A: Detsika, B: Stilla, C: Peska.

orrelation between formation thickness and average spacing of the schistosity (Fig. 4). Locally, the formation is seen to thin away from the hinge areas of large F_2 folds (Fig. 5). The base of the flagstone is sharply defined by a series of 10 to 30 cm thick layers of coarse-grained biotite schist, intercalated with bluish-black quartzites. In the eastern part of the area, the same type of succession is repeated approximately 10 m up in the flagstone unit. The upper contact of the flagstone is transitional into bedded psammites with a diffuse and widely spaced schistosity.

Depending on location within the deposit area, slabs tend to come out in thicknesses ranging between 7 and 30 mm. Within a specific quarry area, the range is more limited, dividing the deposit into 'thin-slab' and 'thick-slab' areas, according to the above-mentioned lateral variations in formation and slab thickness. However, individual beds within a quarry may show lenticular shapes, giving a mesoscopic variation in slab thickness but within a narrower range than on the regional scale.

D_2 structures such as small- and large-scale thrusts, thrust-bend folds, biotite-rich shear-bands and a shear (C)-foliation in micaceous layers (Fig. 6) are connected to the thrusting during the early stages of the deformation. How-

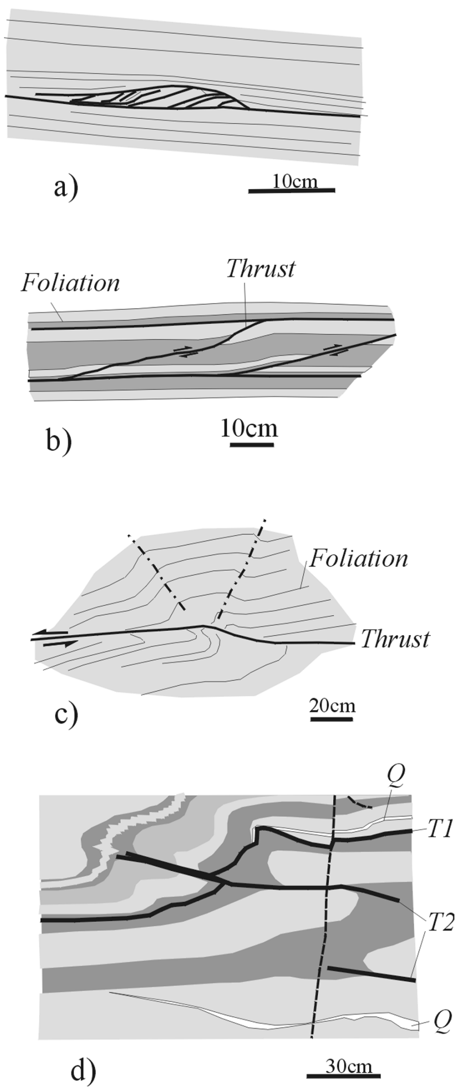


Fig. 6. Minor D2 structures from the Alta flagstone. (a) small, boudinaged duplex, (b) minor thrusts which are rooted and roofed in along the S-foliation planes, (c) minor thrust with thrust-bend box fold, and (d) polyphasal thrusting and folding (early thrusts (T_1) are folded and cut by later thrusts (T_2) developing from the folds). Q=quartz veins.

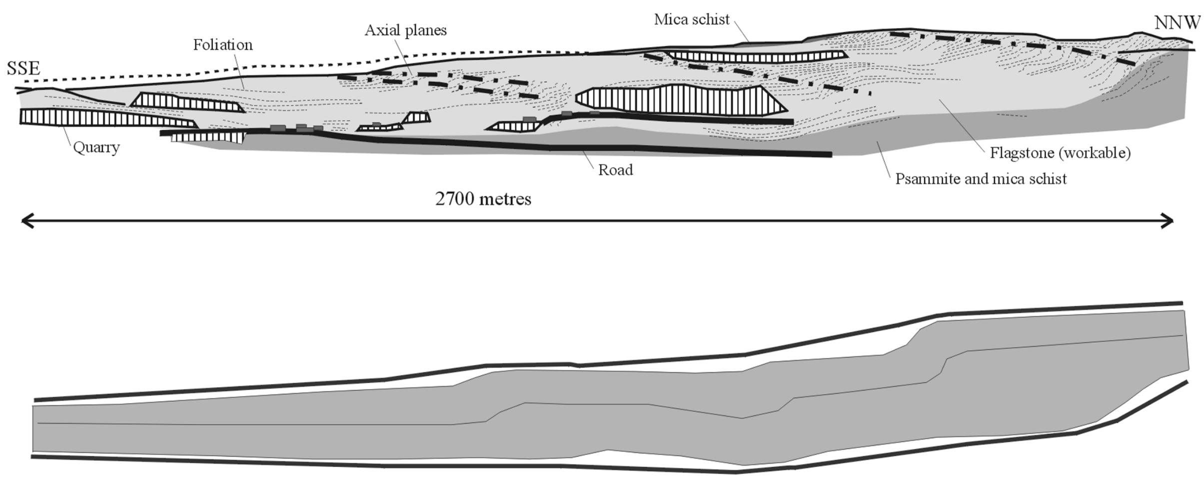
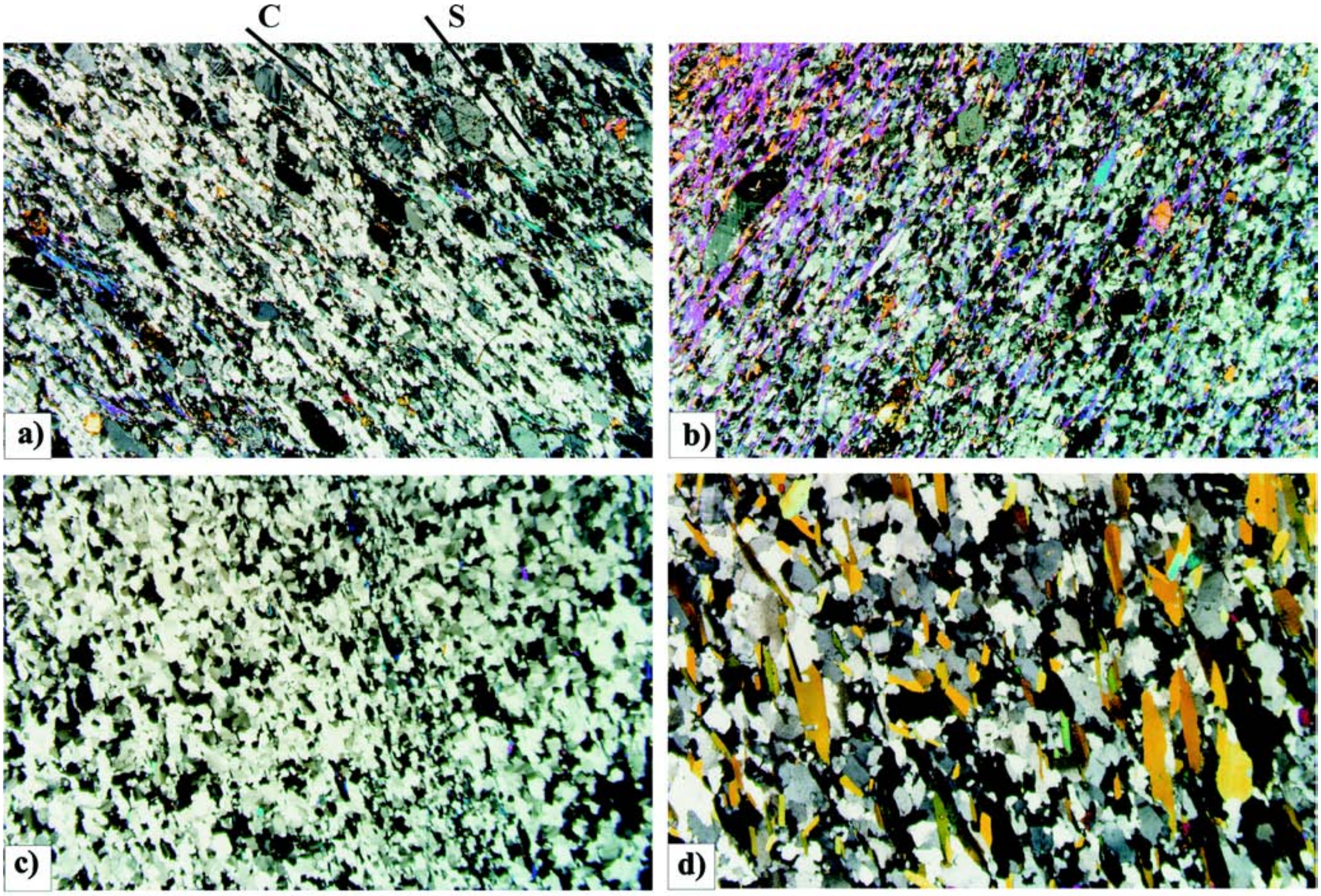


Fig. 5. Sketch profile of the Peska deposit area, Alta, seen from the east. The flagstone unit can be seen thinning towards the south, away from early fold structures, as illustrated in the lower drawing.



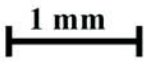


Fig. 7. Photomicrographs of flagstone textures, crossed polars. Scale bar applies for all images. (a) Annealed mylonitic, S-C texture from a mica-poor variety of the Alta flagstone (S and C foliations are marked). (b) Annealed mylonitic, S-C texture from a mica-rich variety of the Dovre flagstone. (c) Quartzitic flagstone from Dovre, cleavage plane to the right of centre. (d) Typical granoblastic texture from the Oppdal flagstones. (e) Granoblastic-elongate texture from the Engan variety of the Oppdal flagstones. Concentrated mica laminae represent cleavage planes.

ever, boudinaged fold hinges, pinch-and-swell structures and circular spots of altered residues of sulphides and/or oxides indicate a change from essentially pure shear to a simple shear regime towards the end of the D_2 episode.

Two intercalating subtypes of flagstone are observed, one which has an almost entirely quartzofeldspathic composition in between the mica laminae (Fig. 7a) and one with abundant lepidoblastic mica. The latter is generally preferred among quarrymen, since the 'armouring' mica makes the rock more elastic and less brittle and fractured than the former.

The texture of quartz in thin-sections (Fig. 7a) is classified as porphyroclastic, annealed mylonitic (Spry 1969), where granoblastic-elongated grains occur in almost fibrous, parallel aligned (S_2) aggregates averaging 0.1 mm in thickness. The alignment coincides with the NW-SE stretching lineation, L_2. Feldspars occur as larger, rounded porphyroclasts, up to 1 mm in size. Lepidoblastic micas (less than 1 mm long) are oriented within S_2 or, alternatively, along shear-bands (C-foliation) at approximately 15° to S_2. Quartz aggregates are sporadically seen parallel to the latter mica orientation, but the dimensional orientation of the grains generally follows S_2, indicating a late-D_2 annealing along S_2.

Thus, both field relations and microtextures indicate that the formation of the schistosity during D_2 is the result of simultaneous flattening and shearing/thrusting, terminating in an episode of gravitational flattening which overprinted and rotated shear (C)-structures. All in all, the generally very low-angle to almost parallel relations between S and C structures indicate an extreme thinning of the flagstone formation.

The Dovre flagstones

The *Dovre flagstone* deposit is situated at Storvassberget, approximately 20 km NE of the village of Dovre in Gudbrandsdalen. The flagstone unit belongs to the extensive psammitic-quartzitic sucsessions in the pre-Ordovician Heidal Group (Strand 1951, Sturt et al. 1991), within the Otta Nappe (Sturt et al. 1997). The Heidal Group rests unconformably upon the Høvringen gneiss, which represents the basal part of the nappe. On top of the Heidal Group, above a primary, depositional unconformity, are the low-grade phyllites of the Middle Ordovician Sel Group. Locally, rocks of ophiolitic affinity (the Vågåmo Ophiolite) occur between the two metasedimentary successions, having been thrust on top of the Heidal Group in Early Ordovician times, prior to the deposition of the Sel Group (Sturt et al. 1991).

The emplacement of the Otta Nappe is of Scandian age, and occurred under middle greenschist-facies metamorphic conditions. However, it has been shown by Sturt et al. (1997) that the Heidal Group had already attained a medium-grade mineral paragenesis prior to sedimentation of the overlying Sel Group. Within the Heidal psammites, flagstone is locally developed along shear zones, related to thrusts or to the sheared contacts between different rock units, and in the long limbs of early folds. In the Storvassberget area, the Heidal Group thins out towards N-NE, and the rocks in the area are generally intensively deformed. The productive flagstone unit occurs sandwiched between the underlying Høvringen gneiss and an overlying, locally developed, thrust sheet of the same gneiss (Fig. 8). Thus, the lower contact of the flagstone may represent a tectonically modified primary unconformity whilst the upper boundary is a thrust.

The base of the flagstones is well exposed, and quartz-mica mylonites are seen resting upon phyllonites and phyllonitic augen gneiss. These mylonites grade upwards into workable, grey flagstones with a well developed, spaced foliation (10-30 mm). The upper part of the flagstone unit consists of dull white, quartzitic flagstones, with a markedly lower content of mica and feldspar than in the grey variety.

The internal structures of the flagstone are strongly reminiscent of those described from Alta. Individual beds show pinch-and-swell structure, with corresponding variation in slab thickness (Fig. 9). We have, however, insufficient observations to reach any conclusion regarding lateral variations in the formation thickness, due to the lack of outcrops.

In thin-section, the texture and grain size of the grey flagstone appears quite similar to the Alta flagstone (Fig. 7b), but the relict mylonitic fabric of the quartz aggregates is less obvious. The texture of the quartz in the Dovre flagstones may, more correctly, be described as granoblastic-elongate. As in Alta, elongate quartz aggregates follow the NW-SE, L_2 stretching lineation, and a C-foliation locally develops a S-SE dipping intersection lineation on the schistosity surface (Fig. 10). Thus, the D_2 structures at Dovre may indicate a slightly lower, but still significant, degree of thinning than at Alta, or

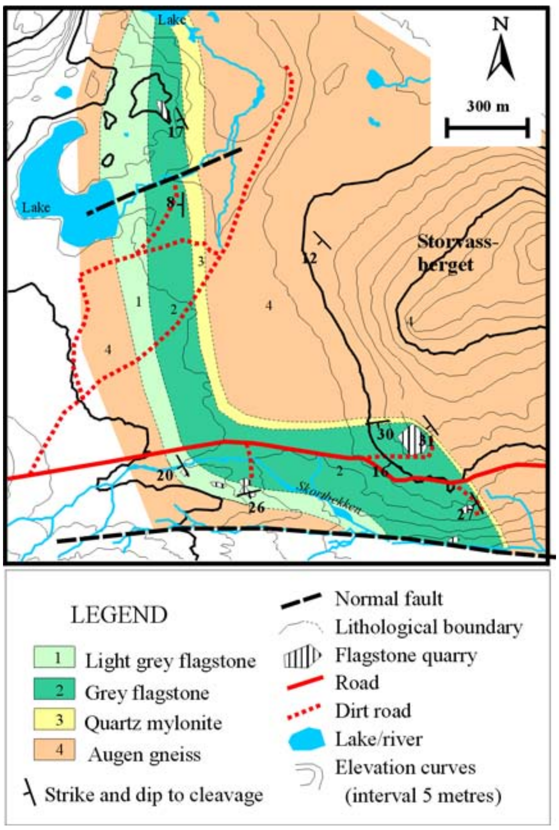


Fig. 8. Geological map of the Dovre flagstone deposit (from Heldal & Sturt 1997).

Fig. 9. Pinch-and-swell of individual beds within the Dovre flagstone deposit.

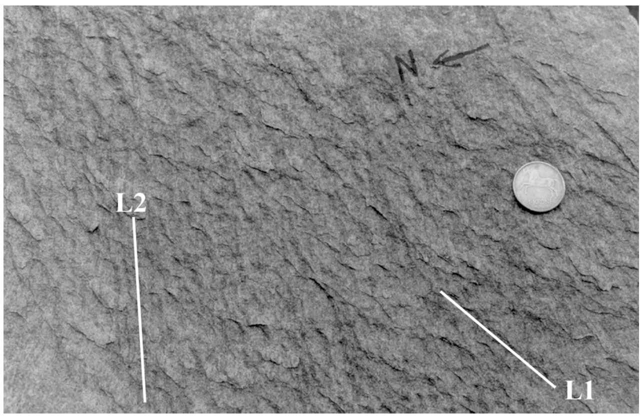


Fig. 10. Lineations in the Dovre flagstone. L_1=S-C intersection lineation, L_2=stretching lineation.

alternatively, a stronger overprinting of D_2 textures during later deformation. However, we have no observations that indicate any significant overprinting textures corresponding with the orientations of D_3 structural elements.

The upper, dull white flagstones differ significantly from the grey ones, consisting almost entirely of quartz, with only minor amounts of feldspar and lepidoblastic mica (Fig. 7c). Even on the schistosity surface, the micas do not form continuous layers. This obviously reflects the fact that there is a limited amount of mica-forming material available in a pure quartzite. Quartz occurs in the pure quartzitic parts between the mica laminae as < 0.4 mm diameter grains with a granoblastic, annealed texture. In the micaceous laminae, however, the grain size is smaller (0.1 mm) and the aggregates show a higher degree of preferred orientation. This indicates a stronger post-tectonic annealing in the former case.

On the natural stone market, the quartzitic flagstones are considered to be a highly interesting product due to their almost white colour. However, as has been shown, the schistose properties are poor, and the very low content of mica makes the rock brittle and closely jointed.

The Oppdal flagstone

The *Oppdal area* involves an autochthonous and parautochthonous Palaeoproterozoic basement with younger sedimentary cover sequence, overlain by a series of Caledonian nappes composed of Proterozoic and Early Palaeozoic rocks (Krill 1980 and 1986, Fig. 11). The flagstone deposits occur within the Sætra Nappe, which consists primarily of highly deformed psammites of Neoproterozoic age. Deformed dolerite dykes are abundant in the Sætra Nappe; the lack of such dykes in the other rock units in the area led Krill (1980, 1986) to conclude that the Sætra Nappe is completely allochthonous in the Oppdal area and can possibly be correlated with the Särv Nappe further east (Gee et al. 1985).

Krill (1980) concluded that the thrusting which gave rise to the tectonostratigraphic succession of the area took place during the early stages of the main Caledonian (Scandian) orogeny. Later deformation and metamorphism obscured these early structures and the rock units were folded in major, recumbent folds. The flagstone quarries shown in Fig. 11 are located in the inverted, highly strained limb of such a recumbent antiform. The superimposed, latest stage of structural evolution includes upright folding, and both reverse and normal faulting.

The workable flagstones in Oppdal occur at several separate levels with intervening non-workable psammites and laterally extensive folded layers. This pattern of quite pronounced vertical variations in quality reflects either an inhomogeneous distribution of strain or primary sedimentological features, or both, where the folded layers may reflect primary variations in rheology between the layers.

The slab thickness (20 – 50 mm) of the Oppdal flagstones is generally greater than in the other two deposits. However, a few exceptions exist, and in the Engan area (Fig. 11) (Lund et al. 1998) the spacing of the schistosity approaches the typical range of the Alta and Dovre deposits, namely 8-20 mm. This is explained by a regional thinning of the flagstone formation.

In thin-section, the 'average' Oppdal flagstone is markedly coarser grained than at Alta and Dovre (Fig. 7d). Quartz occurs as grains up to 0.8 mm in size, in a granoblastic to granoblastic-elongate texture. Feldspars are essentially of the same size, except in sporadic gritty layers. Lepidoblastic micas approach 14 mm in size. The Engan type of flagstone is more fine grained (quartz less than 0.2 mm), and a bimodal

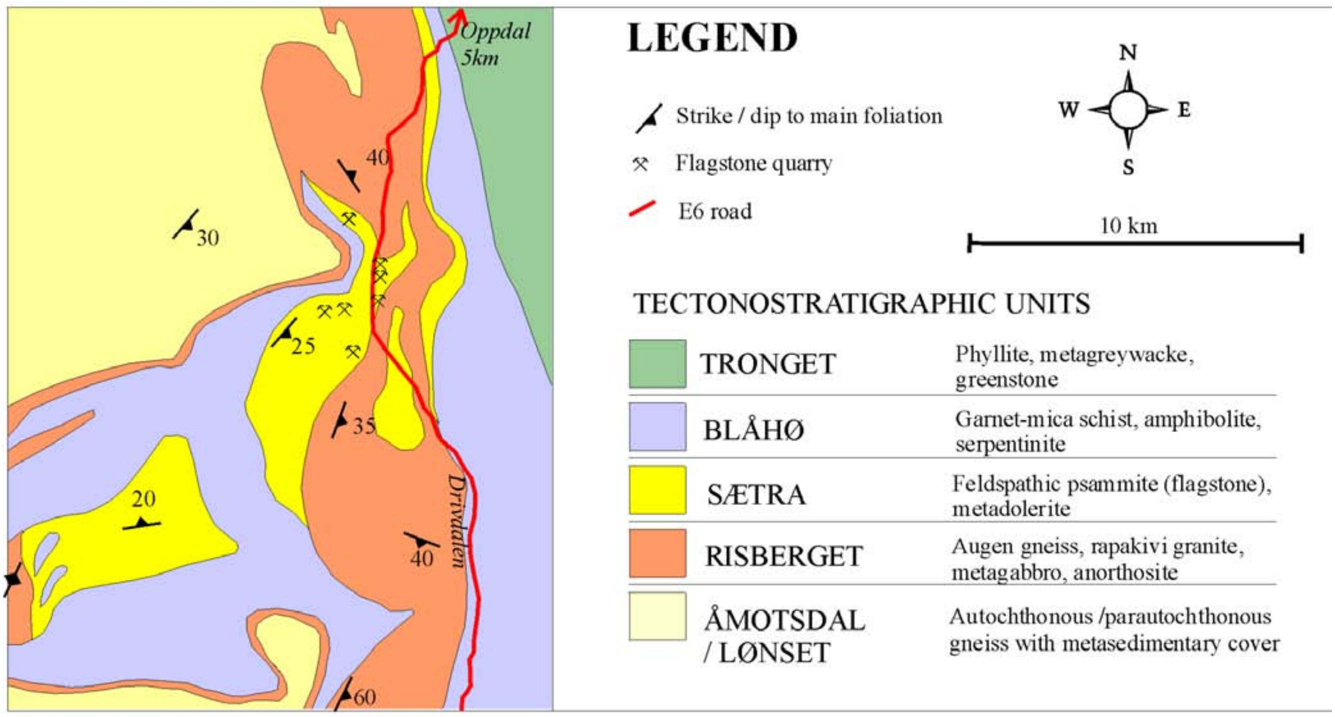


Fig. 11. Geological map of the Drivdalen flagstone quarries, Oppdal, and main lithological units in the surrounding area (after Krill 1980).

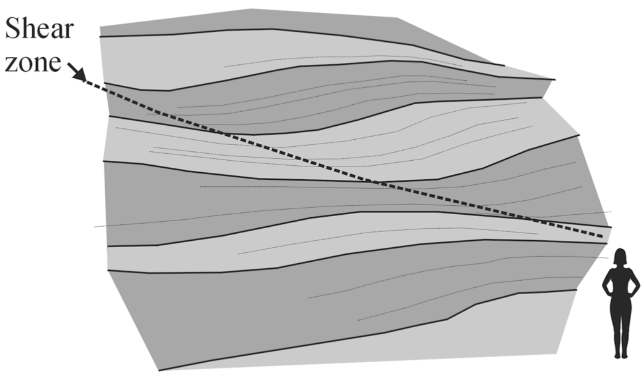


Fig. 12. Pinch-and-swell of flagstone beds in the Oppdal flagstone deposit, with the development of asymmetric lenses close to a low angle shear zone.

grain-size distribution between quartz and feldspars is seen (Fig. 7e). The quartz texture is still granoblastic-elongate, but with a tendency towards a higher degree of preferred orientation than in the average flagstone. The overall impression of the Oppdal-type flagstone is that the grain size and texture are closer to those in a primary 'sandstone-fabric' than at Alta and Dovre.

Fabrics and quality

'Soft' or 'hard' cleavage

Among quarrymen, it is well known that some flagstones are 'soft' (easy) to cleave, others are 'hard' (difficult). Alta and Dovre (grey) flagstones belong essentially to the former type, and cleaving is done with short chisels. Oppdal is considered to be more difficult, and the workers need to penetrate the whole blocks with long, flat chisels in order to cleave them.

It seems clear that this characteristic of the flagstones is attributable to deformation grade and metamorphic differentiation. The 'soft' types have a very sharply defined planar structure (S_2), are very fine grained with larger porphyroclasts of feldspar, and have a granoblastic-elongate to annealed mylonitic texture. The 'hard' flagstones have a coarser grain size, and granoblastic to granoblastic-elongate texture with more evenly distributed, lepidoblastic mica throughout the quartzofeldspathic layers. There are no significant differences in the grain size for quartz and feldspar, except in gritty layers where there are larger porphyroclasts of feldspar. Thus, when the rocks become more anisotropic as a consequence of increasing strain, the cleaving properties, not surprisingly, improve.

The quartzitic flagstones at Dovre, however, are difficult to cleave for additional reasons. The content of mica is actually too low to give a good cleavage. This reminds us of the basic fact that arkoses and/or sandstones with a pelitic component are necessary protoliths for 'producing' a flagstone deposit of acceptable quality.

Slab size

The obtainable size (area) of flagstone slabs is of great importance in exploitation, since large slabs generally give a better waste ratio in the quarries than small ones. Slab size is closely related to jointing and, thus, also to the intensity of later deformation, i.e. close spacing of joints gives small slabs. However, jointing is not only a function of tectonics and stress release, as the rheology of the rocks is also of vital importance. For flagstones, rocks with a closely spaced foliation and low content of mica are generally more conspicuously jointed than mica-rich flagstones with a widely spaced foliation. The micas contribute in 'armouring' the slabs and reducing the brittleness of the rock, a feature that is highly appreciated by the quarrymen.

Slab thickness

The thickness of slabs, corresponding to the spacing of the schistosity or cleavage, shows both vertical and lateral variations in the deposits. A gradual, vertical variation is seen clearly at Alta and Dovre. In the former case, slab thickness increases upwards in the upper part of the commercial unit, until non-commercial psammites are reached. At Dovre, there is a transition at the base of the unit from fissile, non-commercial flagstone with very closely spaced cleavage (less than 5 mm) into the commercial types with slab thicknesses reaching more than 10 mm. In both cases, this can be linked to the degree of relict mylonitic fabric in the rocks. The picture is not that obvious at Oppdal, where there are more rapid, cyclic changes between folded layers, thick-slab layers and thin-slab layers.

The lateral variations correspond to variations in thickness of both individual layers and slabs ('edging slabs') and the flagstone units themselves. On a mesoscopic scale, thickness variations of flagstone beds are seen in most quarries, where the thicker areas have essentially a wider spacing of the foliation than the thinner, thus indicating that these variations are strongly related to strain. In many cases, these structures seem to be connected to the late flattening deformation, resulting in pinch-and-swell structures. This was combined with high layer-parallel shear strain, particularly around the 'swell' areas. Early fold hinges are commonly observed in such areas, indicating that early folds were important in controlling such structures. However, there are also observations supporting the view that pure shear was a more dominant factor in the formation of lateral thickness variations of flagstone beds. One example is shown in Fig. 12, showing how the development of a shear zone has instigated formation of 'fish'-shaped beds.

Pinch-and-swell structure in the flagstone units as a whole would appear to have similar explanations, as shown in Fig. 13. At Alta, the correspondence between lateral thinning of the formation and slab thickness is, as shown above, quite clear. Thus, there are several indications that slab thickness appears to be a function of strain, and that both lateral and vertical variation in strain can have been quite significant within any one deposit.

Importance of linear fabrics

L_2 intersection lineations are mainly found in the Alta and Dovre areas, where it results from the intersection of shear foliation with the penetrative micaceous S_2 surface. This

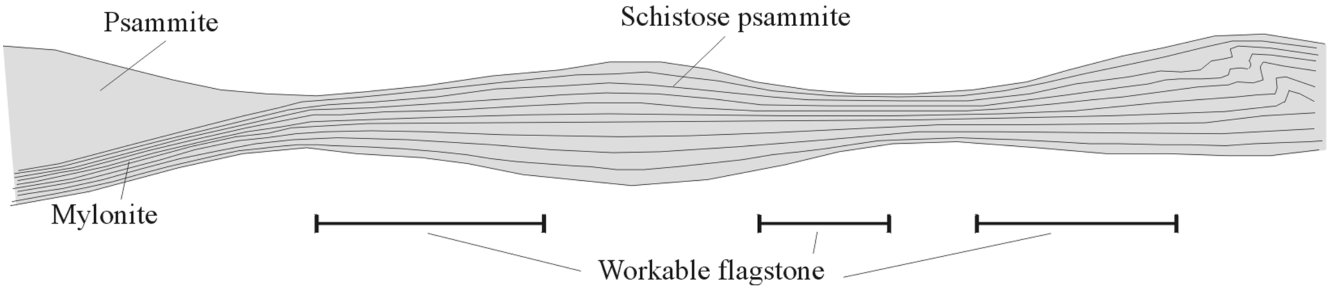


Fig. 13. Schematic model for lateral variations of slab thickness and formation thickness within a flagstone deposit.

gives the S_2 surface a 'tiled' appearance reminiscent of slickensides. The most obvious consequence for quarrying is that the slabs are more easily cleaved along these 'slickensides' than against them. The L_2 stretching lineation is a distinct feature of all three deposits. It commonly consists of elongate aggregates of micas and quartz, and quartz rods. This lineation is the second strongest anisotropic feature of the flagstones, and makes the best direction for primary blasting and vertical splitting of slabs.

Fabrics and physical properties

As experienced in practical use and shown in physical testing, the Oppdal flagstone has a higher water absorption value than those of Alta and Dovre, implying that larger volumes of water more easily penetrate the pore spaces of the rock. This has practical consequences for the flagstone, i.e. even thin slabs of the Oppdal flagstone are not considered to be suitable as roofing material, as a rock with higher water absorption is generally more vulnerable to frost action than less porous rocks. The present study establishes that the highly strained and mylonitic flagstones are less porous than the less strained flagstones, since the grain-size and layer thickness reduction during mylonitisation contribute to reduction in the pore volume. Similar conclusions were reached in an earlier study on the durability of natural stone (Alnæs 1995).

A positive consequence of higher porosity are the excellent cutting properties of the Oppdal flagstones. After engraving a shallow groove along a straight or curved line on the cleaved surface, the slabs can be broken with a straight edge along the line. This enables low-cost production of blocks for cladding. The Alta and Dovre flagstones cannot be treated in this way, and must be cut by sawing.

There are also marked differences in the polishing properties of the flagstones. Even though the colour of the naturally cleaved surfaces is medium grey for all three flagstone types, Alta and Dovre turn dark grey, almost black, when polished, while Oppdal turns light grey. This may be explained by the porosity and grain size. Smaller grains and a better cohesion between the grains gives a darker colour to polished surfaces. Another consequence of the low porosity in the Alta and Dovre flagstones is that they are much harder and more expensive to cut and polish than Oppdal, even where mineral contents, by volume, are approximately the same.

There are notable, but not significant variations in bending strength and crushing strength between the rocks of the deposits. Again, the Oppdal flagstone occurs at the lower end of the scale, probably due to its porosity. However, the directional differences are greater in the Alta and Dovre flagstones, due to the strong linear anisotropy developed in these rocks.

Conclusions

The three flagstone deposits, and other similar deposits within the Norwegian Caledonides, are preferentially developed close to thrusts or in the strongly flattened and sheared long limbs of major folds. Characteristically, metamorphism was in middle or upper greenschist facies. Such conditions were favourable to the development of the kind of foliation and mineral growth necessary for a workable flagstone deposit.

Flagstones from Alta, Dovre and Oppdal are superficially similar when viewed in buildings or pavements. However, as a result of differences in respect of workability in quarry and factory and other in service requirements, they can be categorised into two main groups: 1) the *essentially* mylonitic flagstones from Alta and Dovre, and 2) the *essentially* granoblastic Oppdal flagstones. This is a reflection of the fact that the metamorphic flagstones represent different stages along a line of low-grade, dynamothermal metamorphic development from moderately high to very high strain, where the average varieties of Oppdal and Alta represent the two end-members. Based on the textural and structural differences, it is possible to relate a number of important 'technical' properties of the flagstones to the degree of strain and to erect a simple classification scheme such as shown in Fig. 14. The 'low-strain' end-member is characterised by thicker slabs, poorer cleavability, higher porosity and water absorption, lower strength and (most likely) a better ability for transverse breakage than the 'high-strain' variety. In all three deposits, there are significant lateral and vertical variations in strain, leading to quite rapid changes in the quality of the deposits from unexploitable psammites through paving-quality to roofing-quality flagstone. Thus, one can find sub-types of flagstone in the Oppdal area reminiscent of the average quality of Alta and Dovre, and vice-versa. This is a feature one should bear in mind when investigating other deposits or looking for new ones. A professional mapping of important structural features and structural characterisation of the rock

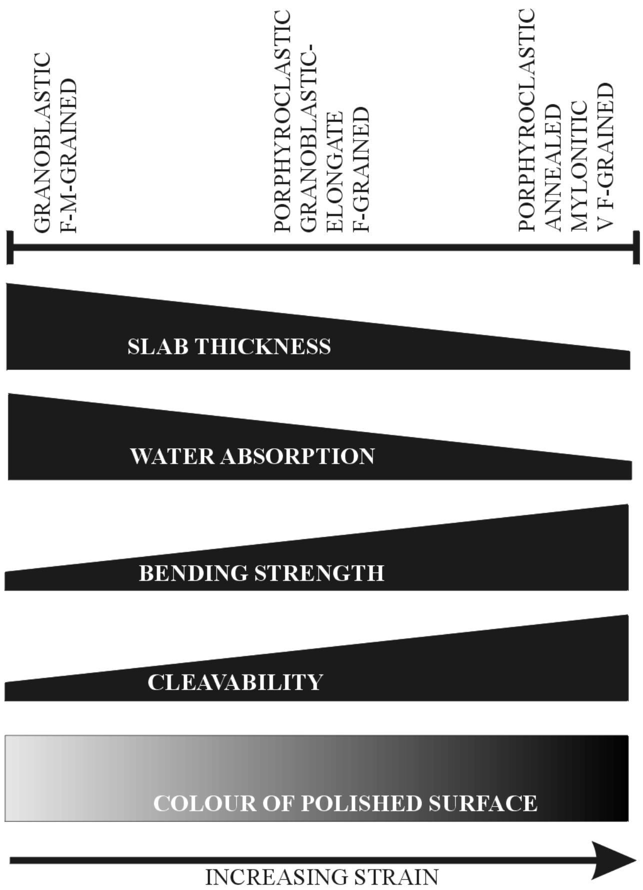


Fig. 14. Textures and quality aspects of flagstones and their variations according to the degree of strain.

would, necessarily, increase the possibility of predicting subsurface deposit quality as well as properties of importance for the user.

In addition to the strain-dependent variation in cleavability, most of the problems that the quarrymen encounter are related to the overall structural pattern in the area. Product type, production yield, blasting and splitting directions and surface appearance are all factors that are related to the interaction of several deformational episodes and can be systematically described and interpreted in order to increase the predictability of subsurface flagstone quality.

Acknowledgements

The authors wish to thank Stensliperiet and Altaskifer AL, Alta, Skifer & Naturstein avd. Dovre and Skifer & Naturstein (avd. Oppdal), for sharing their experience on working and using flagstone, and for their good support during fieldwork. We would also like to express our gratitude to several geologists who, during the last decades, have investigated flagstone deposits in Norway, including David Roberts, Per Ryghaug, Klaas B. Zwaan, Odd Øvereng and Jan Egil Wanvik. Donald Ramsay, David Roberts, the late Brian Sturt, and Alvar Braathen are acknowledged for critically reading the manuscript.

References

Alnæs, L. I. 1995: *Kvalitet og bestandighet av naturstein. Påvirkningsfaktorer og prøvemetoder*. Dr.Ing. thesis, Norges Tekniske Høgskole, 420 pp.

Gee, D. G., Guezou, J. C., Roberts, D. & Wolff, F. C. 1985: The central-southern part of the Scandinavian Caledonides. In: Gee, D. G. & Sturt, B. A. (eds.) *The Caledonide orogen – Scandinavia and related areas*. John Wiley & Sons, Chichester, 109-133.

Guezou, J. C. 1978: Geology and structure of the Dombås-Lesja area, Southern Trondheim Region, South-Central Norway. *Norges geologiske undersøkelse 340*, 1-35.

Heldal, T. & Sturt, B. 1996: Skifer ved Storvassberget, Dovre kommune. *Norges geologiske undersøkelse Rapport 96.097*, 16 pp.

Heldal, T., Zwaan, B., Tegner, C., Holst, B. & Karlstrøm, H. 1997: Geologiske undersøkelser av Altaskiferen. *Norges geologiske undersøkelse Rapport 97.064*, 111 pp.

Krill, A. G. 1980: Tectonics of the Oppdal area, Central Norway. *Geologiska Föreningens i Stockholm Förhandlingar 102*, 523-530.

Krill, A. G. 1986: Eidsvoll quarry, Oppdal, South Norway: a one-outcrop model for some aspects of Trollheimen-Dovrefjell tectonics. *Norges geologiske undersøkelse Bulletin 404*, 23-32.

Lund, B. 1979: Geologisk kartlegging og vurdering av skiferressurser innenfor Dovre skiferindustris konsesjonsområde ved Hornsjø-Storvassberget, Dovre kommune. *Norges geologiske undersøkelse Rapport 1745*, 17 pp.

Lund, B., Heldal, T. & Nissen, A. 1998: Geologiske undersøkelser av Oppdalskiferen. *Norges geologiske undersøkelse Rapport 98.044*, 21 pp.

Ramsay, D.M., Sturt, B.A., Zwaan, K.B. & Roberts, D. 1985: The Caledonides of northern Norway - a tectonostratigraphic overview. In: Gee, D.G. & Sturt, B.A. (eds.) *The Caledonide Orogen - Scandinavia and related areas*. John Wiley & Sons, Chichester, 163-184.

Roberts, D. 1985: The Caledonian Fold Belt in Finnmark: a synopsis. *Norges geologiske undersøkelse Bulletin 403*, 161-178.

Spry, A. 1969: *Metamorphic textures*. Permagon Press, 352 pp.

Strand, T. 1951: The Sel and Vågå map-areas. *Norges geologiske undersøkelse 178*, 1-116.

Sturt, B. A., Ramsay, D. M. & Neuman, R. B. 1991: The Otta Conglomerate, the Vågåmo Ophiolite - further indications of Early Ordovician orogenesis in the Scandinavian Caledonides. *Norsk Geologisk Tidsskrift 71*, 107-115.

Sturt, B. A., Ramsay, D. M. & Bjerkgård, T. 1997: Revisions of the tectonostratigraphy of the Otta-Røros tract (extended abstract). *Norges geologiske undersøkelse Bulletin 433*, 8-9.

Sturt, B. A. & Ramsay, D. M. 1997: The Gudbrandsdalen Antiform - a major late Caledonian structure (extended abstract). *Norges geologiske undersøkelse Bulletin 433*, 12-13.

Sturt, B. A., Bøe, R., Ramsay, D. M. & Bjerkgård, T. 1995: Stratigraphy of the Otta-Vågå tract and regional stratigraphic implications (extended abstract). *Norges geologiske undersøkelse Bulletin 427*, 25-28.

Zwaan, K.B. & Ryghaug, P. 1972: Råstoffundersøkelser i Nord-Norge. Geologisk kartlegging i Alta. *Norges geologiske undersøkelse Rapport 1035-11*, 23 pp.

Zwaan, K. B. & Roberts, D. 1978: Tectonostratigraphic successions of the Finnmarkian nappe sequence, North Norway. *Norges geologiske undersøkelse Bulletin 343*, 53-73.

Zwaan, K.B. & Gautier, A.M. 1980: Beskrivelse til de berggrunnsgeologiske kart 1834 I og 1934 IV, M 1:50 000. *Norges geologiske undersøkelse 357*, 1-47.

Zwaan, K.B., Cramer, J.J. & Ryghaug, P. 1975: Råstoffundersøkelser i N-Norge. Berggrunnskartlegging i forbindelse med geologisk ressursinventering. *Norges geologiske undersøkelse Rapport 1118-1*, 77 pp.