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SEDIMENTARY CHARACTERISTICS, BRITTLE STRUCTURES AND PROSPECTING METHODS OF THE FLAMMET QUARTZITE

a feldspathic metasandstone in industrial use from the Offerdal Nappe, Swedish Caledonides

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ABSTRACT

This thesis deals with the sedimentary characteristics, brittle structures, and prospecting methods of the Flammet Quartzite (loc. Offerdalsskiffer), a dimension stone quarried in the Swedish Caledonides. The two main areas of emphasis are firstly the exploration in an area of no bedrock exposure, and secondly the assessment of the deposit.

The Flammet Quartzite is quarried within the Offerdal Nappe at the Landögssjön area, in the county of Jämtland, Sweden. The Offerdal Nappe belongs to the lower part of the Middle Allochthon of the central Scandinavian Caledonian thrust belt, and contains three tectonostratigraphic units separated by thrust displacement. The Offerdal Nappe is correlated with the riftogenic Risbäck paleobasin. The Risbäck basin is characterised by coarse clastic sediments dominated by fluvial deposits passing laterally into lacustrine and various marine facies. The extracted rock material is derived from subunit D of the local stratigraphy of the Finnsäter region, which belongs to the lower part of The Upper Tectonostratigraphic Unit (UTU) of the Offerdal Nappe. Subunit D is composed of feldspathic metasandstone with a sharply defined compositional layering differentiated into cleavage domains and microlithons. The cleavage domains are characterised by oriented phengitic muscovite and microcrystalline quartz, and the microlithons are made up mainly of recrystallised quartz and feldspar. The cleavage has an average frequency of 4 cleavage planes/10 mm. The thickness of the cleavage domains varies between 0.5 to 1.5 mm with crenulation amplitudes of up to 0.5 mm. The persistency of parallel series of cleavage planes can be traced for several meters (> 5 m).

Fracture studies within the Nya Finnsäter quarry have defined 3 main fracture sets. Mean direction of orientations are 277/85,149/89 and 208/86 with an estimate of mean fracture trace length of 4.4 m, 3.4 m and 8.0 m respectively. Fractures oriented along 208° and 149° occur in fracture zones that are generally traceable along the full length and width of the Nya Finnsäter quarry (more than 150 m). Based on the presence of larger continuous fracture zones, it is possible to predict fracture frequencies in non-accessible areas (i.e. areas covered by drift material). By extrapolating fracture traces from a small mapping window a rough picture of the geometry of the local fracture system can be obtained. For example, in a trench 30 – 50 m long and 1 m wide excavated down to bedrock, a valid fracture prognosis can be made extending 14 m to either side of the trench.

The fracture prognosis also takes into consideration natural and induced fractures. Two types of fracture occurrences related to blasting have been defined; type A coalescing fractures with at least one end terminating in a drill hole, and type B coalescing fractures with one end terminating in a type A fracture. Fractures of type A increase the fracture frequency to 23 %, type A and B together increase the fracture frequency to 36%. In this investigation, approximately 17 % of the rock volume shows increased fracturing from the blasting operation.

Keywords: Cleavage, cleavage domains, microlithons, induced fracturing, natural fracture system, dimension stone quarry, Flammet Quartzite, Offerdalsskiffer, Offerdal Nappe.

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Paper I: Loorents, K.-J., 1997: Petrology, brittle structures and prospecting methods in the "Offerdalsskiffer" from the central part of the Caledonian Allochthon in the county of Jämtland, Sweden. Thesis for Licentiate degree. Earth Sciences Centre, Göteborg University, A21, 67 pp.

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Paper III: Loorents, K.-J. and Stigh, J.: Cleavability in relation to mineralogy and deformation in feldspathic metasandstones from the Offerdal Nappe, Swedish Caledonides. Manuscript submitted to GFF.

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Paper V: Loorents, K.-J., Björklund, L. and Stigh, J.: Induced fracturing based on a characterised fracture system in a dimension stone quarry in the Offerdal Nappe , Swedish Caledonides. Accepted for publication in Bulletin of Engineering Geology and the Environment. Reprinted by permission of Springer-Verlag, Heidelberg.

Preface

This thesis, submitted for the doctoral degree at Göteborg University, is based upon the five papers listed below. The thesis relates results concerning the Offerdal Nappe in general and the Flammet Quartzite dimension stone in particular. Hans Svensson, Skifferbolaget AB and Lisbeth Godin-Jonasson SAF (earlier Utvecklingsfonden in the County in Jämtland) initiated the project together with co-ordinators Prof. Jimmy Stigh and Dr Lennart Björklund at the Earth Sciences Centre, Göteborg University. The main sponsors of the project have been the Skifferbolaget AB, Länsstyrelsen in the county of Jämtland, NUTEK and Teknikbrostiftelsen in Umeå.

List of papers

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Introduction

Skifferbolaget AB has for well over 30 years quarried the Flammet Quartzite, locally known as the "Offerdalsskiffer" (Lundegårdh, 1971). The rock has been quarried in several quarries around lake Landögssjön, county of Jämtland, central Sweden, and nowadays mainly within the Finnsäter area (Figs. 2 and 4 in Paper I). The Flammet Quartzite dimension stone is used as a landscape- and decorative stone, but also as different building materials. Uncut slabs are mainly used as landscape- and decorative stones and the cut slabs as floor tiles, treads, risers, skirtings and wall claddings.

Variations in sedimentologic and structural characteristics occur in the Flammet Quartzite and cause some parts of the formation to be unsuitable for use. Prior to 1993, rock was classified simply as "good" or "bad" based on perceived characteristics. A growing concern about the lack of geological background knowledge during the mid-1980's gave rise to several attempts on the company's behalf to identify potential new localities of raw material within the Landögssjön area. Field mapping was done by Persson (1980) and later by Kallin (1989). However, by the end of the 80's, most of the known reserves did not meet the production demand. In early 1993, a meeting was announced with participants from Utvecklingsfonden County of Jämtland, Swedish Geological Survey (SGU), Norwegian geological Survey (NGU), Göteborg University, Trondheim University and Skifferbolaget AB. The meeting pointed out the lack of geological maps of the area. Due to this, a regional geological mapping of the Landögssjön area was carried out by SGU (Stephens et al. 1993) paid for by the county administration (Länsstyrelsen) in Jämtland. Simultaneously with this regional mapping, Skifferbolaget AB, SGU and Göteborg University formed a surveying group in order to locate new findings of the Flammet Quartzite. Based on regional mapping, structured prospecting work, and open discussions, a new finding of high-quality raw material was located in late 1993. This finding ensured the survival of the company Skifferbolaget AB. The prospecting process and the opening of the Nya Finnsäter quarry (Fig. 4, Paper I) has clearly demonstrated the feasibility and value of a systematic prospecting method.

Smith (1999) describes the general aims and objectives of exploration for dimension stone. Exploration should be done stepwise. First, locate a target resource, verify the quantity and quality together with the economics of the extraction. Next, the costs of processing, planning and environmental issues, including any further processing of the material, need to be resolved. The main reason why there was a shortage of resources and reserves in 1993 was the lack of such a structured plan of geological exploration.

Production of the Flammet Quartzite is a matter of understanding complex geological and industrial processes. Therefore, it has been considered necessary to study large-scale structures – the Offerdal Nappe, as well as small scale structures, such as the location of a single fracture.

The rocks of the Offerdal Nappe in the Landögssjön area are of a sedimentary origin (Kumpulainen and Nystuen, 1985, Stephens, 1993). The primary sandstone was deposited either as a homogeneous unit or as a layers composed of sand and clay. Metamorphic processes and sheering has formed the tectonic cleavage characterising the Flammet Quartzite.

The Finnsäter (Figs. 2 and 4 in Paper I) exploration area is characterised by gently rolling hills with very few bedrock exposures. This low availability has forced the development of a field methodology to describe the fracture system locally. Due to the generally highly fractured bedrock, the extraction method had to be evaluated concerning also the fracturing induced by the quarrying process. If the bedrock exposure has a high natural fracture frequency, a minimum of induced fracturing can be allowed. This means one needs to find the distinguishing characteristics for profitable and non-profitable areas early on during exploration.

Paper I

Loorents, K.-J., 1997: Petrology, brittle structures and prospecting methods in the "Offerdalsskiffer" from the central part of the Caledonian Allochthon in the county of Jämtland, Sweden. Thesis for Licentiate degree. Earth Sciences Centre, Göteborg University, A21, 67 pp.

Three main topics were studied; the regional geology, the spatial distribution of the quarried section, and the characterisation of the Flammet Quartzite concerning mineralogy, texture and brittle structures. Paper I presents the detailed stratigraphy of the Finnsäter area and the geological description together with a study of brittle structures within the Finnsäter quarry. Furthermore, an applied field mapping method for areas of little or no bedrock exposures was introduced.

The quarrying of the Flammet Quartzite is located in the Offerdal Nappe (Gee et al.1985) of the Landögssjön area (Fig. 4 Paper I). The Offerdal Nappe belongs to the lower part of the Middle Allochthon of the central Scandinavian Caledonian thrust belt. The contact zone with the underlying Lower Allochthon displays a significant structural discordance. Vendian to Silurian sedimentary rocks of the Lower Allochthon (Gee and Zachrisson, 1979; Stephens and Gee, 1989) are discordantly overridden by the Offerdal Nappe, implying significant, late, out-of-sequence movements on the basal Offerdal Thrust (Palm et al., 1991). Shear sense indicators suggest thrusting of the Offerdal Nappe towards the east southeast, which is similar to the over- and underlying nappes. The eastward displacement exceeds at least 150 km (Gee, 1978). The upper part of the Middle Allochthon in the Landögssjön area belongs to the Särv Nappe (Strömberg et al., 1984). The contact zone between the Offerdal Nappe and the overlying Särv Nappe is the basal Särv thrust marking a change in lithology. The thickness of the Offerdal Nappe at the Landögssjön area is estimated to vary between 1 to 2 km (Stephens et al., 1993).

The rocks of the Offerdal Nappe are correlated with the riftogenic Risbäck paleobasin (Kumpulainen and Nystuen, 1985). The Risbäck basin is characterised by coarse clastic sediments dominated by fluvial deposits passing laterally into lacustrine- and various marine facies, containing many minor unconformities within the sequences. During the Caledonian orogeny, these rocks were structurally transported eastwards as part of the Offerdal Nappe.

Stephens et al. (1993) divided the Offerdal Nappe into three tectonostratigraphic and five lithostratigraphic units (Figs.2 and 3 in Paper I). *The Lower Tectonostratigraphic Unit* (LTU) consists of the Offerdal Conglomerate. It is displayed as an array of flat-lying lenses, mainly along the southern and western margin of the Offerdal Nappe. *The Middle Tectonostratigraphic Unit* (MTU) is sub-divided into two lithostratigraphic units: MTU 1 and MTU 2. The main lithologies of the MTU are feldspathic- and fine-grained metasandstones. Within the western part of the Offerdal Nappe (Fig.2 in Paper I), the MTU consists both of MTU 1 and MTU 2 (Fig.2 in Paper I). MTU 1 is mainly built up by thick-layered feldspathic metasandstones interbedded with mica-rich phyllites. MTU 2 on the other hand is dominated by a fine-grained metasandstone, locally with carbonate-rich layers. *The Upper Tectonostratigraphic Unit* (UTU) is sub-divided into two lithostratigraphic units: UTU 1 and UTU 2. The metasandstones of the UTU 1 have a generally well-developed foliation, with a general cleavage spacing between 1-3 cm. The UTU 2 is dominated by thick-layered metasandstones, with a layering generally thicker than 3 cm.

Three deformational events have been distinguished within the Offerdal Nappe (Stephens et al., 1993). The D_1-deformation includes all structures formed during the eastward Caledonian transport. This event took place at a deeper crustal level, relative to the following events of deformation. The later D_2-deformation deforms the D_1-foliation and related structures. The latest phase of deformation (D_3) formed structures under semi-ductile to brittle conditions, including kink bands and fractures. The D_3 probably represents late- to post-Caledonian deformation.

Minerals formed during the Caledonian thrusting include epidote, white micas, biotite and garnet. This mineral assemblage indicates upper greenschist facies within the major part of the Offerdal Nappe.

Recent quarrying has been located on the western limb of the Offerdal synform (Fig. 2 in Paper I) and in particular to the Finnsäter area. The quarries within the Finnsäter area expose the feldspathic metasandstones belonging to the lower part of UTU (Stephens et al. 1993). The Finnsäter stratigraphy comprises five slightly different flaggy metasandstones (A – E). Quarries within the area encompass subunits C to E. The lowermost subunit C is a thin-layered to laminated feldspathic metasandstone characterised by a pale green-grey colouring. A distinct transition zone 1 – 2 m thick separates subunit C from subunit D. The subunit D is an up to 15-m thick succession of a thin-bedded to laminated grey feldspathic metasandstone. An approximately 10-m thick portion of subunit D is used for the commercial quarrying. The contact-zone between subunit D and subunit E, which can be up to 5-m thick, is characterised by a gradual change into a less-pronounced foliation. The subunit E is composed of a thin layered, dark-grey feldspathic metasandstone.

The average modal mineral composition of the Flammet Quartzite analysed by point counting, contains 44 % quartz, 35 % phengitic muscovite, 11 % alkali feldspars, 7 % epidote, 2 % biotite, and 2 % calcite. Accessory minerals are sphene, Fe-Ti oxides, chlorite, apatite and allanite. A more detailed SEM-EDS modal analysis of cleavage domains and microlithons has been done and is presented in Table 3 in Paper I.

As the Nya Finnsäter quarry provided the largest rock exposures of the Flammet Quartzite, the main effort on brittle studies has been located to this quarry. The initial study has been based on a scanline survey (Priest, 1993), which reviled the presence of three main fracture sets. The fracture sets have mean orientations of 277/85,149/89 and 208/86. The estimated mean fracture trace lengths are 4.4 m, 3.4 m and 8.0 m. Fractures oriented along set 208° and also along set 149° show a tendency to appear in fracture zones. These fracture zones are generally traceable along the full length and width of the Nya Finnsäter quarry.

Paper II

Plink-Björklund, P., Björklund, L. and Loorents, K.-J.: Basin analysis of the late riphean metasediments of the Offerdal Nappe, Swedish Caledonides – a prospecting tool for dimension stone. (manuscript)

This paper aims to describe the sedimentological conditions of the Flammet Quartzite, and to interpret the spatial relationships of the sedimentary sequences and depositional environments of the Offerdal Nappe rocks. The metasedimentary origin of the Offerdal Nappe has been documented by Kumpulainen (1982), Kumpulainen and Nystuen (1985) and Stephens et al. (1993), with the Nappe geometry described in Stephens et al. (1993). The rocks of the Offerdal Nappe are metamorphosed and tectonically deformed which limits the interpretation of a sedimentological study. The main problems are to distinguish between sedimentary structures from structures related to tectonic deformation, and also to differentiate sedimentary grain size from metamorphic grain size.

The depositional model suggests a basin with fan conglomerates at its southeastern margin. Sand that bypassed these fans accumulated in subaqueous fans to the northwest. Later, alluvial or delta deposition followed at the eastern margin, and sand accumulated on a storm dominated shelf. Braided stream deposits finally filled the basin.

The sedimentological analysis suggests the occurrence of Flammet Quartzite to represent distal turbidite lobe deposits, forming subaqueous fans. This interpretation is suggested by rocks that show a distinct alternation between thick quartz-and feldspar-rich zones and thin mica domains. These layers have sheet-like geometry with contacts that are flat like unscoured bedding surfaces.

Paper III

Loorents, K.-J. and Stigh, J.: Cleavability in relation to mineralogy and deformation in feldspathic metasandstones from the Offerdal Nappe, Swedish Caledonides. Manuscript submitted to GFF.

The Flammet Quartzite is marketed as pieces with sawn edges such as floor tiles, treads and wall claddings, and also pieces of special measure e.g. mantelpieces. A large part is sold as "crazy stones" (flagstone) i.e. a less planar slab with uncut edges, mainly used as landscape stones. The attributes of the rock are related to mineralogical composition and to the grade of metamorphism. However, a very important economical criterion is the ability to split the rock into a preferred thickness. Economical raw materials of metasandstones, suitable for splitting and producing slabs have specific cleavage properties. The characteristics of the cleavage, e.g. frequency, thickness and variability will decide the range of finished products. Thickness and variability determine the slab's surface texture and the frequency the thickness of the cleaved slabs. This paper presents a detailed study of cleavability based on a comparison of rocks from subunit C to E, of the local stratigraphy of the Finnsäter region.

The rocks from subunit C to E within the Finnsäter stratigraphy (see Paper I) form a compositional layering (Fig. 7 Paper I and Fig 3 Paper III) differentiated into cleavage domains, defined as planar structures containing fabric elements subparallel to the trend of the domains (Passchier and Trouw, 1996), and microlithons, defined as the area bound by two cleavage domains (Passchier and Trouw, 1996). The cleavage domains are characterised by oriented phengitic muscovite and microcrystalline quartz, and the microlithons are mainly made up of recrystallised quartz and feldspars.

In order to quantify the textural parameters in the feldspathic metasandstones of economical importance, subunit D has been compared to the subunits C and E. The initial comparison has been based on drill core samples from these subunits (Fig 3 Paper III). The textural parameters are mapped from photographs displaying the lateral surface area. At a higher level of resolution the same kind of comparison based on thin sections was done (Fig. 3 Paper III).

To map the spatial distribution of the cleavage domains within subunit D, several drill cores (12) were collected from a block obtained from the Nya Finnsäter Quarry within subunit D. The block was drilled according to figure 4 in Paper III. The cleavage for each drill core was mapped on photographs displaying the lateral surface area, and then interpolated between the samples according to figure 4 in Paper III.

The Flammet Quartzite is quarried within subunit D. The cleavage of this subunit is characterised with an average frequency of 4 cleavage planes/10 mm. The thickness of the cleavage domains varies between 0.5 to 1.5 mm, with amplitude of up to 0.5 mm. Plane persistency with parallel planes can be traced for several meters (> 5 m). Subunit C has an average frequency of 2 cleavage planes/10 mm. Cleavage domains vary in thickness between 0.5 to 3.5 mm, with an crenulation amplitude of the cleavage domains varying up to 1.5 mm. Plane persistency is the same as for subunit D. Subunit E has an average frequency of 1.75 cleavage planes/10 mm. Cleavage domains are generally thinner than 0.5 mm. The crenulation amplitude of the cleavage domains is << 0.5 mm. The plane persistency is less continuous than compared to subunits C and D.

It can be concluded that only one part of subunit D conforms to the textural prerequisites, of frequency, thickness, variability and plane persistency of the cleavage domains that characterise an economical potential reserve for the Flammet Quartzite for the present range of production.

Paper IV

Loorents, K.-J., Stigh, J. and Björklund, L., 2000: Characterisation and prediction of a fracture system based on a sited excavated ditch in the Offerdal flaggy metasandstone, Central Caledonides, Sweden. Bulletin of Engineering Geology and the Environment, vol. 58, no. 2, pp. 159 – 165. Reprinted by permission of Springer-Verlag, Heidelberg.

The characterisation of a fracture system is associated with properties of individual fractures, such as their orientation, size, termination, roughness and curvature, as well as the properties of the fracture system, such as fracture frequency and geometry (Priest, 1993). A certain degree of bedrock exposure is needed to map these structural properties. In general, the more data collected the better the understanding of the fracture system (Davis, 1986). Structural mapping is an essential part of the evaluation when making decisions where to locate an extraction site and on maximizing the recovery ratio (Smith, 1999). Where large bedrock exposures occur this is straightforward, but it is more problematic where there are only limited exposures. This paper discusses a method to estimate the fracture system in bedrock of economical interest using sited excavated ditches to supplement the information obtained from core drilling. The relevance in using this adapted mapping method has been tested for it's potential as a tool for characterisation and prediction (see Paper I).

Due to the coverage of drift material, which can vary in depth between 1.5 – 6 m within the Finnsäter exploration area (see Paper I), no bedrock exposures are available. As a fracture analysis is imperative to estimate the block size distribution, an adapted ditch mapping method had to be used in order to predict the fracture system. The mapping method was based on excavated ditches. The location and orientation of these mapping ditches were based on information from drill core logs and earlier fracture surveys within the Nya Finnsäter quarry.

The mapping ditch used was approximately 1 m wide at the rock surface and 30 – 50 m long. By extrapolating fracture traces mapped along the ditch, a rough prediction of the geometry of the local fracture system was obtained. This is valid due to the existence of larger persistent structures such as continuous fracture zones and kink bands, which can be traced for a distance longer than that of the extrapolated fracture trace map. It also implies that an extrapolated fracture trace map is not sensitive enough to detect a local small scale fracturing. Thus the ditches will only give limited spatial information about the fracture system. For the Finnsäter survey area, a prediction regarding fracture frequency is valid up to 14 m from the ditch.

Highly fractured areas can be predicted by using continuous structures such as fracture zones and kink bands. This is especially true for areas where fracture sets intersect or for areas containing conjugate structures, e.g. in the present paper kink bands and fracture zones.

Paper V

Loorents, K.-J., Björklund, L. and Stigh, J.: Induced fracturing based on a characterised fracture system in a dimension stone quarry in the Offerdal Nappe, Swedish Caledonides. Accepted for publication in Bulletin of Engineering Geology and the Environment. Reprinted by permission of Springer-Verlag, Heidelberg.

In Paper I (cp. Paper II and 3) it has been shown that potential reserves for the production of the Flammet Quartzite are restricted to a ca 10-m thick section (subunit D). The main survey and quarry area is located in a region of very limited bedrock exposure (see Paper IV). The limited spatial distribution of potentially economical raw material for the production of the Flammet Quartzite, and the topography of the region makes it costly to open several quarries. Thus a greater degree of fracturing is acceptable as long as the overall recovery rate is economically justified. Under these conditions it has been considered valuable to connect the fracture survey to the extraction method, i.e. to investigate the influence of the extraction method on the fracture prognosis. This paper discusses a method to distinguish between natural and induced fractures, where the induced fractures are caused by the extraction method.

In the Nya Finnsäter quarry, extraction of rough blocks is done by bench blasting, with a maximum bench height of up to 3.55 m. The bench is drilled slightly tilted from the horizontal to be aligned with the main tectonic foliation (cleavage) using a hole diameter of 35 mm spaced 0.50 m apart. Due to the location and the size of the bench, the number of drill holes varies. Holes are charged with a mixture of Prillit and granulate together with Gurit (Nitro Nobel Dyno Explosives Group, 1996), and 0.90 m drill cuttings are used as a stemming.

The degree of the induced fracturing has been estimated by comparing two surfaces both mapped by window sampling (Priest, 1993). The two surfaces differ in that one contains natural fractures and the other contains both natural and induced fractures. The surfaces have been compared according to fracture set orientation, fracture size, and fracture frequency. One area located within the Nya Finnsäter quarry (Figs. 1 and 2) constituted the quarry floor at the time of mapping. This area contains natural and induced fractures. A second area located about 200 m north northeast of the first one, is situated in an area where no quarrying have been done. The later surface is considered to contain only the natural fracture system.

Two types of fracture occurrence related to blasting have been defined; type A with coalescing fractures with at least one end terminating in a drill hole, and type B with coalescing fractures with one end terminating in a type A fracture. Fractures of type A increase the fracture frequency with up to 23 %. Taking fractures of type A and B together this results in an increase of up to 36%. Approximately 17 % of the rock volume shows increased fracturing from the blasting operation. However, these results suggest that an analogous significantly increased fracturing by blasting may be expected and detected in other dimension stone quarries.

Discussion

As noted in Smith (1999) "Geologists are interested in the origin, composition, structure and geological history of the earth and, unless they are applied geologists, are not usually concerned with their practical use: geology is a science, not a technology. Architects, structural engineers and civil engineers, by contrast, are interested in rocks as construction materials and are not usually concerned about any of their other attributes." However, the present work demonstrates that successful prospecting and economic excavation of dimension stone is critically dependent on a combination of "scientific" geological factors. This is well illustrated by the great differences in cleavability compared to the subtle differences in appearance for the untrained eye of the metasandstones of the Offerdal Nappe. The differences are the result of geologic processes.

The Flammet Quartzite is a feldspathic metasandstone characterised by a well-developed cleavage. The ability to split the rock along the foliation is the single most important factor for its use as a dimension stone, shared with an array of other metasandstones used as construction materials (Mehling et al 1993). The ability to cleave well and the character of the cleaved surface depend on the primary sedimentary character and the specific conditions of later mineralogical and textural reworking.

Sandstones suitable as dimension stones may originate in a wide range of depositional environments. The sedimentary facies of the Altaschist, a dimension stone quarried in Finnmark region, Norway, is interpreted to be one characterised by massive feldspar-rich sands (Heldal et al., 1997), while the Flammet Quartzite is interpreted to have originated as well laminated metasandstones and mudstones in a distal turbidite deposit (Paper II). The depositional model for the Flammet Quartzite is consistent with the smooth, continuous, parallel foliation with a general spacing of 2.5 mm throughout the quarried section. In contrast, the Altaschist shows a greater variation in the foliation; the mica domains have a thickness of 0.5 – 2 mm and a spacing of 10 – 20 mm. Geologic mapping (Stephens et al., 1993) combined with facies identification, lateral distribution mapping and sequence stratigraphic interpretation serve to effectively delimit the area of prospecting and increase its cost-effectiveness.

Characterising parameters such as surface texture of the split rock, plane parallelism, frequency and thickness of the cleavages are dependent on the environment of the primary deposition, as well as the mineral composition, texture and grade of metamorphism. These parameters are decisive but dependent on the quality requirements set by economic and industrial demands. For example, thicker, more uneven sheets with rougher cleavage surfaces are acceptable for production of the less-expensive paving stone. Detailed stratigraphic knowledge is thus a prerequisite for a cost-effective use of the reserves. Detailed description of the mineralogy and cleavage properties of the Flammet Quartzite is crucial because it has been sold on the international market for many years, and is expected to have a specific surface texture, colour, size and thickness, depending on the product. Thus, a reserve for the Flammet Quartzite must exhibit certain geological attributes to be of industrial and economical interest.

Field mapping combined with statistical methods within well-exposed areas, i.e. pit quarries, has a well-established methodology (Priest, 1993 and Smith, 1999). However, this approach has not been applicable to areas without bedrock exposures. The low frequency of bedrock exposure within the Finnsäter area strongly limits collectable data. This introduces an uncertainty in a fracture prognosis. The establishing of a block quarry within an area where drift material range between 2 – 6 m of thickness is only economically motivated if detailed knowledge of the local brittle and ductile structures is available, and that a potential economical stratigraphic unit is located. This is the case within the Finnsäter area where regional- and local geological mapping, combined with an extensive array of drill cores (Stephens 1993, Paper I), has confirmed the location, quality and volume of a reserve.

Even when a substantial volume is located, very little is known of the potential recovery rate. To provide estimates of recovery rate, fracture mapping is needed, either by drill core mapping or obtaining a rock exposure. Fracture mapping using drill cores is not a practical option as it is very hard to obtain intact drill cores. This is mainly due to the well-developed subhorizontal foliation as well as the presence of fracture zones. Another option is to get access to a larger mapping window by clearing off the drift material. This approach is commonly considered too costly. The general depth of the drift material in the area may cause the economic recovery rate to be lower than the costs of clearing off the drift. Against this background, the applied field mapping methodology, e.g. ditch mapping, has been favoured, because the amount and quality of data can be economically justified. In Paper IV it is shown that the applied field mapping methodology has the potential to produce a usable prognosis about the fracture system. This type of prognosis requires the presence of larger structures such as fracture zones, continuous kink bands and a detailed knowledge about the present fracture system.

The critical importance of fracture mapping, as described in Paper V, is emphasised because both natural and induced fractures are present. Mapping the influence of the extraction method and connecting that information to the fracture survey enables a more accurate prognosis of the recovery rate. Adjusting the extraction method, e.g. by alternating between blasting and wire sawing, may increase the recovery rate, or even mean the difference between a profitable or non-profitable extraction in the Finnsäter area.

Fracture mapping done by ditch or as high-resolution window mapping is costly and time consuming. It is the author's belief that the methods described here can apply to other areas in the world where bedrock exposure is limited and the distinction between natural and induced fractures is crucial. This field mapping methodology is generally motivated in areas and situations similar to the Finnsäter area, where a specific type of dimension stone, cleaved or massive, with a limited spatial distribution is sought.

Conclusions

The rock material extracted and used for the production of the Flammet Quartzite is derived from the subunit D within the Finnsäter stratigraphy, and is interpreted to represent distal turbidite lobe deposits. This subunit D at the Landögssjön area belongs to the lower part of the UTU 1 of the Offerdal Nappe of the Middle Allochthon of the Scandinavian Caledonides. Subunit D is composed of a feldspathic metasandstone with a layering differentiated into cleavage domains and microlithons. The cleavage domains are composed of oriented phengitic muscovite and microcrystalline quartz and the microlithons are mainly made up of recrystallised quartz and feldspars. The cleavage has an average frequency of 4-cleavage planes/10 mm. The thickness of the cleavage domains varies between 0.5 to 1.5 mm, and with an crenulation amplitude of up to 0.5 mm. Plane persistency with parallel planes can be traced for several meters (> 5 m).

The study of brittle structures within the Finnsäter survey area has shown three main fracture sets. The mean direction of orientation and dip are 277/85, 149/89 and 208/86, with an estimate of mean fracture trace length of 4.4 m, 3.4 m and 8.0 m respectively. Fractures of set 208° and to some degree set 149° show a tendency to appear as fracture zones. These fracture zones are generally traceable along the full length and width of the Nya Finnsäter quarry.

Based on the presence of larger continuous structures it has been showed that it is possible to predict fracture frequencies in drift-covered areas. From a mapping window, a ditch 30 – 50 m long and 1 m wide, a fracture prognosis is valid 14 m perpendicular to the ditch in the Finnsäter area.

The possibility of differing between natural and induced fractures has proven to be beneficial for the fracture prognosis in relation to the recovery rate. It is also relevant as an evaluation tool for the efficiency of the extraction method. Fracture analysis has shown significant increase in fracturing of the rock volume related to the quarrying, pointing to the use of alternative extraction methods. Using a fracture-mapping method relevant for block quarrying can significantly improve the quality of data, providing a sensitive tool in exploration and quarry management.

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