Petrographic examination of Norwegian glaciofluvial aggregates: interpretation of mechanisms leading to high contents of cataclastic rocks

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Wigum, B.J. & Jensen, V. 1995: Petrographic examination of Norwegian glaciofluvial aggregates: interpretation of mechanisms leading to high contents of cataclastic rocks. *Nor. geol. unders. Bull. 428*, 33-48.

Norwegian glaciofluvial aggregates have been examined microscopically and classified according to a newly established petrographic method. The results of this study and previous data show that there are high amounts of particles of cataclastic rocks in many Norwegian glaciofluvial aggregates. These rocks are unsuitable because of the expansive effects of such rock-types in concrete, due to alkali-aggregate reactions (AAR). Some interpretations and reasons are put forward to account for the more extensive occurrence of cataclastic rocks in certain areas. Regional examination of glaciofluvial aggregates shows that cataclastic rocks can resist erosion over relatively long transport distances, and that particles within specific size ranges show higher enrichment in these rock-types. It is recognised that the concentration of cataclastic rocks within particular particle fractions is governed by the provenance, distance from the source rock, and the mechanical properties of specific types of cataclastic rocks.

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Introduction

Research into the lithology and transport processes of glaciofluvially derived materials has a long tradition, mainly as a tool for mineral exploration. Most classifications of sand and gravel fractions have usually been done by sieve analysis and binocular microscope. The most commonly used parameters in modern classification and description of glacial deposits are grain size and shape. Pettijohn et al. (1973) pointed out the need for more thin-section studies of sand, by which varieties of lithic fragments can be identified.

Norwegian glaciofluvial sand and gravel deposits have for some years been assessed and classified for their volume and quality, and recorded in computerised databases at the Geological Survey of Norway (Neeb 1993). However, over the last few years there has been a growing awareness of the importance of studying the petrographic and microstructural composition of natural aggregates, mainly glaciofluvial materials used for concrete purposes. This has become necessary in order to meet the more stringent control for detecting aggregate which could exhibit slow/late-expansive alkali-aggregate reactions, which during the last few years has been recognised as a concrete durability problem in Norway (Jensen 1990, 1993, Jensen & Danielsen 1992, 1993, Dahl et al. 1992, Lindgård et al. 1993, Meland et al. 1994).

In concrete, alkali-aggregate reaction is a chemical reaction between sodium and potassium ions in the pore solution and certain types of aggregates. Such types of alkali reactive aggregates contain siliceous components, particularly in the form of microcrystalline and ductile deformed quartz. The reaction forms a hygroscopic alkali-silica gel that can imbibe water and swell. The swelling forces generated may be sufficient to disrupt the surrounding concrete, causing expansion and associated deterioration. In 1992 an optional arrangement for declaration and approval of aggregates for concrete was introduced in

Norway (DGB - Deklarasjon- og Godkjenningsordning for Betongtilslag). It suggests that aggregates should be tested in accordance with the procedures outlined by the Norwegian Concrete Society, publication NB 19 (Norsk Betongforenings Publikasjon Nr.19, 1991). The procedures recommend that the first step should involve testing by petrographic examination of the aggregate. If a low content of reactive or potentially reactive rock-types (<20%) is observed, the aggregate is classified as innocuous with respect to its alkali-aggregate reactivity. If, however, a high quantity of reactive rock-types (20%) is present, the aggregate is classified as reactive. In addition, it is recommended that the aggregate is tested by an accelerated mortar bar test to confirm the reactivity of the aggregate before it is used in concrete structures. Reactive aggregates are not recommended to be used in concrete structures situated in humid environments unless precautions are taken regarding cement type, protection, etc.

At SINTEF Structures and Concrete an improved petrographic method for thin-sections has been developed which has been used successfully to recognise more accurately reactive aggregates (Jensen 1993). This technique has been used to examine a number of glaciofluvial aggregates in Norway. As a result a more accurate picture has emerged with regard to the petrographic and microstructural composition of Norwegian glaciofluvial aggregates. An important feature of the method is that it is able to recognise and classify microstructural features of quartz-bearing rocks. These microstructural features cannot be recognised by ordinary binocular microscope examination. Investigations of a large number of samples from glaciofluvial deposits in Norway have revealed the occurrence of cataclastic rocks in a majority of the samples. Petrographic examination of aggregate from concrete samples obtained from structures suffering from AAR, have also shown a high content of cataclastic rocks. Such rock-types are now considered as the commonest and most widely distributed source of alkali reactive aggregates in Norway (Jensen 1993).

In Norway, due to the intense thrusting and faulting, cataclastic rocks are widely present and therefore should be expected to occur in many glaciofluvial deposits. During the comminution and transportation of glaciofluvial materials, more fragile materials abrade more rapidly, leading to an enrichment (or maintenance of a high level) of quartz-bearing rocks exhibiting high abrasion resistance, in certain fractions in the deposits. The effect will be more marked for longer transport distances.

The aim of this work was to examine the relative occurrence and distribution of cataclastic rocks in Norwegian glaciofluvial materials and to assess various mechanisms and processes which could account for the high occurrence of cataclastic rocks. The provenance, comminution and transportation conditions of glaciofluvial deposits were also taken into account when interpreting the results. Together with the results from SINTEF Structures and Concrete, two further areas were selected for investigation in order to obtain a more detailed picture.

Classification and properties of cataclastic rocks

In order to understand the mechanism which led to enrichment of cataclastic rocks in glaciofluvial deposits it is essential to be familiar with the classifications and properties of such rock-types. All rocks formed by cataclasis are termed cataclastic rocks and are generally felsic and/or silicic in composition. Cataclastic rocks include metamorphic rocks that are deformed at low temperature with primary cohesion due to a combination of crystalloblastic and cataclastic processes. Higgins (1971) has classified cataclastic rocks with primary cohesion into two main categories, depending on whether cataclasis is dominant over neomineralisation-recrystallisation in their formation, or vice versa. Further classification is based

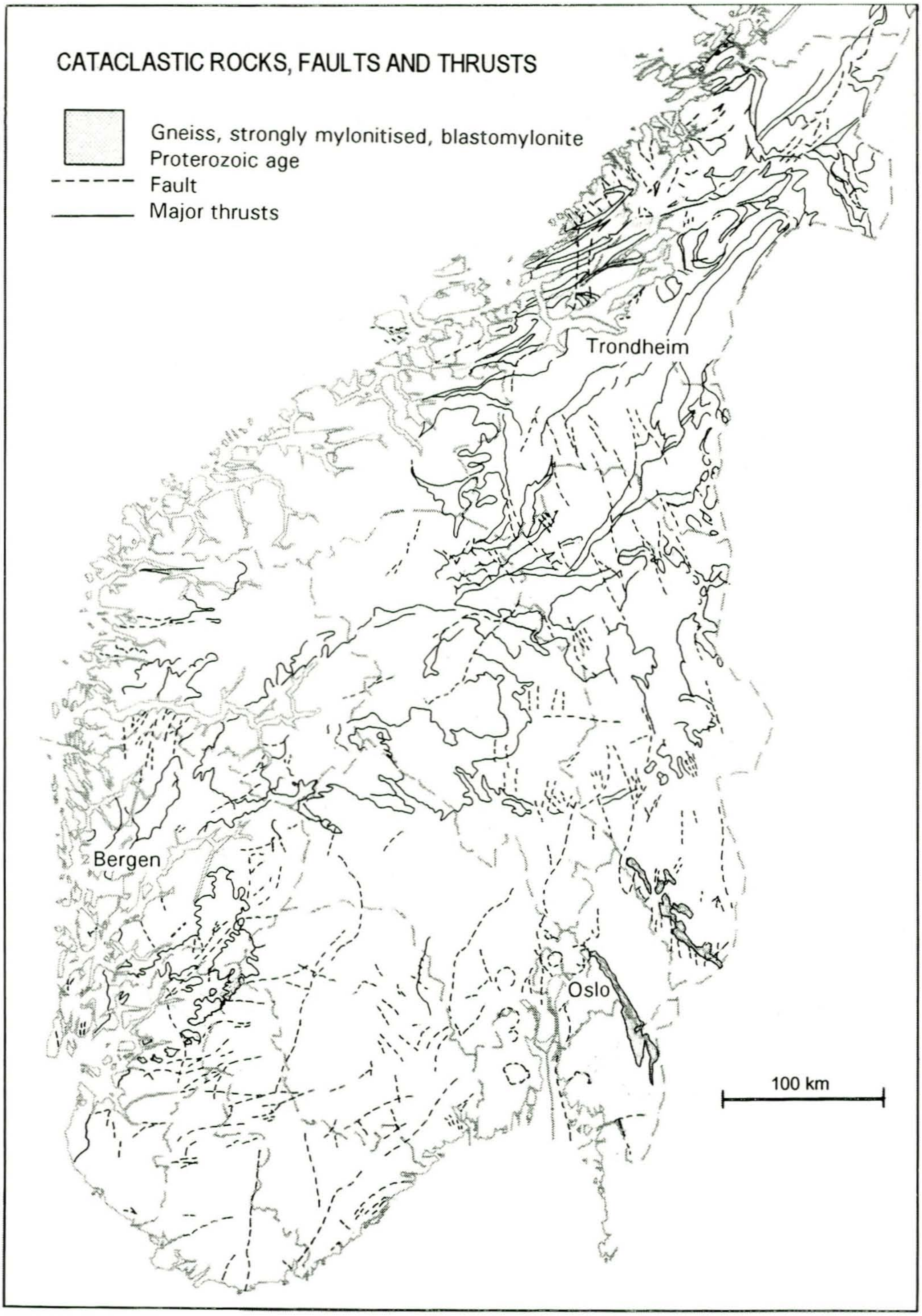

Fig. 1. An outline of mapped cataclastic rocks (mylonite) and major fault and thrust zones in southern Norway (Jensen 1993).

on the occurrence of fluxion structures. Cataclasites are formed under conditions of brittle deformation of the rock, showing random fabric, while various types of mylonites are formed during ductile deformation (flow) of the rock, showing fluxion structures. Fluxion is a synonym for flow, and the term reflects the occurrence of the comminuted matrix of mylonites 'flowing' around the porphyroclasts in layers separated by thin lines marked by concentrations of fine micaceous minerals. Finally, rocks without fluxion structure and cataclasis dominance are defined as microbreccia and cataclasite, while rocks with fluxion structure and cataclasis dominance are defined as protomylonite, mylonite and ultramylonite. Rocks with fluxion structure where neomineralisation is dominant over cataclasis are defined as mylonite gneiss and blastomylonite.

The physical properties of the cataclastic rock are governed by its microstructural features, in particular the state of the quartz. Brattli (1994) investigated the influence of cataclasis on abrasion resistance of granitic rocks. He observed that some types of ductile deformed cataclastic rocks, such as protomylonite, mylonite and ultramylonite, appeared to have extremely high abrasion resistance, while at the same time exhibiting a high brittleness. This was attributed to intense ductile deformation which occurs under relatively low temperatures. Under these conditions, high concentrations of very tightly bounded dislocations are produced in the quartz grains, causing hardening of the minerals, equivalent to cold-working in metals.

Distribution of cataclastic rocks in southern Norway

Cataclastic rocks generally occur in thrust and fault zones resulting from dynamic metamorphism. Fig. 1 shows the outline of mapped cataclastic rocks (mylonite) and major fault and thrust zones in southern Norway where cataclastic rocks may or may not occur. The map has been drawn from the 1:1 mill. bedrock map of Norway (Sigmond et al. 1984). Two larger areas with mapped cataclastic rocks (mylonite) occur in the southeastern part of Norway. These are the Precambrian Mjøsa-Vänern mylonite zone which can be followed into Sweden (to lake Vänern); and further south, the mylonite zone from Øyern to the Swedish border (Oftedahl 1980). According to Oftedahl (1980) the mylonite zones were caused by a series of microcontinental collisions in the Precambrian.

Fault zones occur in many areas of southern Norway, e.g. the southern and southeastern Precambrian regions, the Oslo Region and in the areas of the Caledonian nappes. Thrust zones are also prevalent in many areas, and reflect the extent of the Caledonian overthrusted rocks as a result of nappe transport. The map in Fig. 1 shows that cataclastic rocks are widely distributed in South Norway and should therefore be expected to occur in many glaciofluvial deposits in these areas.

The provenance, comminution, transportation and deposition of glaciofluvial materials

To understand the end product of a glaciofluvial process it is necessary to look at the sedimentary cycle starting with the parent rock at the basal traction zone of glaciers, through transportation in the aqueous environment, to the eventual sedimentary deposit. The origin of glaciofluvial materials is either the bedrock, till or englacial debris. The glaciofluvial materials could be defined as the net result of; plucking and abrasion of lithic fragments in the glacial environment, and modification during recycling in aqueous environments (Slatt & Eyles 1981). These two factors will ultimately influence the final petrographic composition of the glaciofluvial materials. To understand the environmental influence upon the potential enrichment of cataclastic rocks in such materials, these two processes will be discussed further.

Plucking and abrasion of lithic fragments in the glacial environment

In the basal traction zone of glaciers, coarser clasts and sand-size lithic fragments are detached from underlying bedrock surfaces by plucking, abrasion and crushing due to shear stresses exerted by the overriding ice. The physical properties of the rocks and minerals have an influence on their resistance to fracturing. Shear fractures propagate along intracrystal, as well as intercrystal, planes of weakness (Slatt & Eyles 1981). As a result of abrasion, materials beneath the glacier will rapidly be crushed into fine-grained sediments, while plucking might incorporate the loosened bedrock material into the sole of the glacier and then be transported within the glacier. Cataclastic rocks that exhibit very fine quartz grain-sizes, or microstructural features including zones of undulatory extinction, planes of bubble wall inclusions, sub-grain boundaries and water-weakened dislocations, might favour shear fractures along these planes of weakness. On a macroscopic scale, plucking might also exploit pre-existing joints whereby large joint-bounded blocks may be pulled away from the bedrock and incorporated into the glacier (Boulton 1979).

Modification during transportation in aqueous environments

As the material enters the glaciofluvial system it becomes involved in a process of reworking. This reworking is influenced by many factors during subglacial meltwater transportation such as the viscosity of the water which can be high when temperatures are very low. In addition, when there is a combination of heavy load and high velocity flow, then the meltwater can exert an extremely high abrasive action. At lower velocities abrasion is the most important mechanism causing erosion, while cavitations are important at higher velocities. Another important mechanism acting during transport is abrasion due to impinging suspended particles during flow (Lillieskold 1990). Also during glaciofluvial transportation, lithic fragments are subjected to impact-loading, which induces tensile stresses, and which in turn causes extensional fractures to propagate preferentially along intercrystal boundaries (Slatt & Eyles 1981). Harrel & Blatt (1978) found very little size reduction of polycrystalline quartz granules (2-4 mm) during tumbling experiments. They concluded that mechanical durability was inversely proportional to the size of the crystal or grain in an aggregate. Therefore, in a finely polycrystalline particle, the crack path will cross more grain boundaries and grains of different crystallographic orientation. As a result the rate of energy dissipation increases, which in turn leads to a greater hindrance of the crack propagation. This type of behaviour is characteristic of cataclastic rocks as they commonly exhibit very fine grain sizes.

Haldorsen (1982) observed that quartz grains, because of their great mechanical resistance, generally erode to form particles of coarser size fractions than compared for instance to feldspars which have a much lower mechanical resistance. Glaciofluvial materials which originated by erosion of tills were investigated. It was found that the glaciofluvial materials had a sand fraction significantly richer in quartz than the original tills. Results from a grinding test were applied to explain the enrichment of quartz in the sand fraction. It was claimed that glacial transport involves both abrasion and crushing, whereas the glaciofluvial transportation is dominated by abrasion. During abrasion mainly silt is formed. The silt is enriched in feldspar and sheet silicates, and the remaining sand in quartz.

Transportation distance

It is generally agreed that over long transport distances the volume fraction of various grain-size classes of glacial materials is affected by their differential resistance to glacial abrasion. The transport distance is generally greater in glaciofluvial material than in the till from which it is delivered, and thus the source area is more difficult to assess. Further complications are introduced as a result of sorting by water and clast weight. The transport distance might range from kilometres to tens of kilometres, according to the energy level of the glacial meltwater system, the grain size and the resistance of the rocks (Lilliesköld 1990). Most pebbles in glaciofluvial deposits are not particularly far travelled, which explains their relatively poor degree of rounding. In southwest Wales, it has been found that most of the rock-types represented in glaciofluvial deposits are of strictly local origin. There is seldom more than 5% of exotic pebbles which have travelled more than 5 km from their source (Sugden & John 1985). Lee (1965) found that most pebbles in a Canadian esker had travelled less than 10 km from their source, whereas sand and gravel particles had travelled much further.

Deposition

The mode of deposition will control the lithology, the stratigraphy and the facies assemblages. The lithological variation in different beds usually reflects the grain-size distribution (Lilliesköld 1990). It has been reported that subglacial glaciofluvial deposits in eskers have commonly followed zones of structural discontinuity in the bedrock, such as faults (Shilts 1984).

Petrographic method

Most Norwegian alkali reactive aggregates are very fine grained (microcrystalline); therefore identification and classification of aggregate grains cannot be made accurately without the use of thin-section microscopy. In order to obtain more realistic classifications of aggregate for use in concrete, an improved petrographic examination which involves point counting has therefore been developed by SINTEF Structures and Concrete. This method has been used to assess rock constituents in glaciofluvial sands in the present investigation. The preparation of samples of sand for this test is as follows: After sieving, two representative samples of the fractions 1-2 mm and 2-4 mm are selected for further petrographic examination. The samples are then impregnated with an epoxy resin, in order to prepare thin-sections for petrographic examination. Two thin-sections (25 x 50 mm) are made with particles from the fraction 2-4 mm and one thin-section with particles from the fraction 1-2 mm. Approximately 1000 points are counted in each fraction. The volume percentage of reactive rock-types is based on the average of the results from both fractions. A more detailed description of the method is given by Haugen & Jensen (1993) and Lindgård et al. (1993). The classification and identification of the different alkali reactive rock-types are based on; knowledge of past field performance, petrographic nomenclature, and mineralogical and microstructural criteria (Jensen 1993). During microstructural examination the following factors were taken into account; grain-size of quartz, subgrain development in quartz, degree of deformation and recrystallisation. In order to obtain reliable data it is recommended that the petrographic examination is carried out by a geologist who is experienced in identifying reactive rock-types prevailing in that particular country (Lindgård et al. 1993).

In the present work the rocks were classified into the following three main categories in order to simplify interpretation of results and for use in data processing:

Category 1. - Reactive aggregates (with known reactive field performance): sandstones (1), cataclastic rocks (2), acid volcanic rocks (3), argillaceous rocks (4), greywacke (5) and other rock-types with microcrystalline quartz (6).

Category 2. - Potentially reactive aggregates: Quartzite (fine grained*) (7), Other rock-types containing finely divided* quartz (8). *(crystal sizes 0.06-0.13 mm).

Category 3. - Innocuous aggregates: Rocktypes with coarse grains and/or minor amounts of quartz, e.g. volcanic rocks/gabbro (9), granites/gneisses (10), mafic rocks/pure limestone (11) and other rocks (12)

In addition, results from petrographic analyses carried out by SINTEF Structures and Concrete were used to determine the distribution and content of cataclastic rocks obtained from different sources.

Investigated areas

In addition to the results from work by SINTEF Structure and Concrete, we selected two further areas for this study. This ensured data on aggregates sourced from close to and remote from the original parent cataclastic rocks. The work also attempted to compare samples on a regional and local basis, and to compare the difference between different types of cataclastic rocks. In the first investigated area which is part of the southeastern Precambrian province, two major mylonite zones are included, and from the second area, on the Fosen Peninsula, smaller fault zones containing cataclasites are included.

The southeastern Precambrian province

The southeastern Precambrian area lies between the Permo-Carboniferous Oslo Paleorift and the Oslofjord to the west, and the Swedish border to the east. There are two major mylonite zones located in the area (Fig. 5). The northernmost zone is the Mjøsa-Vänern mylonite zone, which lies south of the Solør gneisses and the strongly deformed Odal granites. Further south in this region lies the second mylonite zone, which separates the Romerike grey gneisses (mostly metatonalites) from the Østfold grey gneisses in the south (Oftedahl 1980).

The deglaciation and the glacial deposits in this Precambrian area have been reported by Sørensen (1979, 1983). The Ra moraine in the outer Oslofjord area was formed during the Early Younger Dryas, whereas the second most prominent ice-marginal deposit in the region, the Ski Moraine, was formed at the end of the Younger Dryas. Both the glacial striae older than the Younger Dryas and the glacial striae formed during the Younger Dryas indicate a glacial movement towards the south-southwest in the region.

A total of nine samples containing glaciofluvial aggregates were collected from six different locations within the area. The locations nos. 1 and 2 lie just south and downstream of the Mjøsa-Vänern mylonite zone, with location 3 lying between the mylonite zones, while location 4 was situated along the southern mylonite zone. Locality 5 is situated south of this mylonite zone, at the southern end of lake Øyern. The southernmost location was at the prominent ice-marginal deposit at Mona, which is part of the Ski-Ås moraine complex. At this location four samples were collected (nos. 6 to 9) in order to investigate lithological variations between different layers in the deposit. At the distal part of the ridge, in an approximately 1 m-thick part of the deposit, samples were collected from three different layers; no.6 was collected from a coarse upper layer, no.7 from a 15 cm-thick layer of fine material, while sample no.8 was collected from a medium-coarse layer. Additionally, one sample (no.9) was collected from a coarse layer deep in the middle of the ridge.

Verrabotnen - the Verran Fault

The valley of Skaudalen runs ENE-WSW on the Fosen Peninsula (Fig. 6). The valley was developed along the Verran Fault, forming a topographic lineament running from Rissa to Verrasundet. The fault system near Verrabotnen displays a variety of fault rocks produced by both brittle and ductile deformation (Grønlie et al. 1991). The glacial system has produced an ice-marginal glaciofluvial deposit, Younger Dryas in age, in the valley just west of Verrabotnen (Reite 1994). In most valleys and fjords in this area, glacial striae indicate an ice movement strongly dependent on topographical conditions (Reite 1994). It is therefore believed that the ice moved along Verrabotnen and down Skaudalen to the southwest. A total of three aggregate samples were collected at the ice-marginal glaciofluvial deposit, along the valley profile west of Verrabotnen.

Results

The results from this work and those from petrographic analyses carried out on a commercial basis by SINTEF Structures and Concrete are presented here. Figures 2 and 3 show data analysed from 88 samples which were collected from different locations of glaciofluvial sands in southern Norway. The distribution of cataclastic rocks in aggregate samples from different counties in southern Norway is presented in Fig. 4. The petrographic compositions of the twelve samples investigated in this study are given in Table 1. Further information, such as the locations of the samples, the graphical presentation of some rock assemblages in the 1-2 mm fractions, as well as the ratio of cataclastic rocks between the two fractions, are given in Figs. 5 & 6.

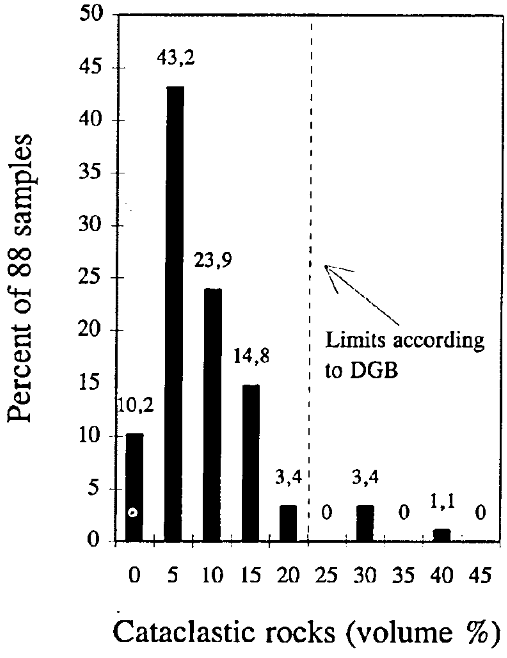

Fig. 2. Cataclastic rocks in glaciofluvial materials in 88 aggregate samples from locations in southern Norway; based on petrographic examination at SINTEF Structures and Concrete 1991-1995.

Discussion

It is necessary to point out that a more accurate interpretation of Norwegian glaciofluvial sand would have been possible if the aggregate samples had been sampled randomly. However, the results presented here will provide a clearer picture about the content and distribution of cataclastic rocks in Norwegian glaciofluvial aggregates. It is evident from Fig. 2 that about 90% of the samples contain various amounts of cataclastic rocks. A high proportion, about 45%, contain 0-5% cataclastic rocks and only a small percentage, about 5%, exhibit greater than 20 % of cataclastic rocks, which also is the limit of alkali reactive aggregates according to the Norwegian optional arrangement for declaration and approval of aggregates for concrete (DGB). Fig. 3 shows the relationship between cataclastic rocks and alkali reactive rock-types. In this figure, cataclastic rocks constituted the majority of all alkali reactive rock-types in several of the samples. In a few samples cataclastic rocks constitute the main component of the alkali reactive rock (plots located on the broken line). The distribution of samples with cataclastic rocks is shown by county region within southern Norway in Fig. 4. The diagram shows that cataclastic rocks are present in varying degrees in samples analysed from all the counties. Generally, the cataclastic rocks constitute less than 20 % of the volume fraction of the aggregate. Aggregate samples from Telemark, Rogaland, Aust-Agder and Møre og Romsdal contain cataclastic rocks which fall into two or less % volume fraction categories. Only samples

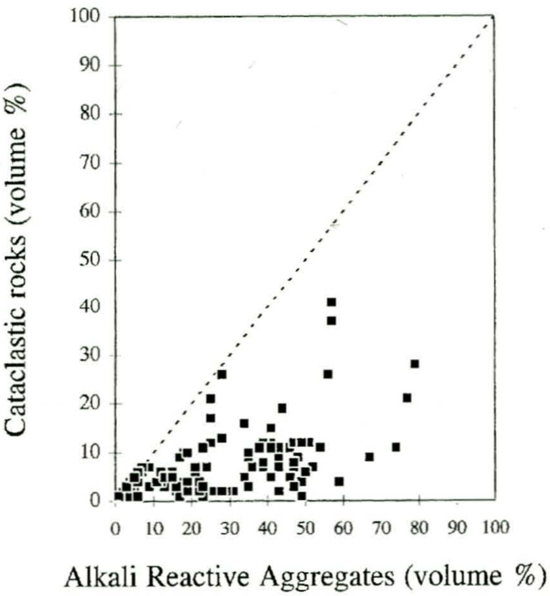

Fig. 3. Relationship between cataclastic rocks and alkali reactive rock-types in 88 aggregate samples from locations in South Norway; based on petrographic examination at SINTEF Structures and Concrete 1991-1995.

from the counties of Sør-Trøndelag and Oppland exhibited cataclastic rocks with a volume fraction greater than 20 %, which is likely governed by local lithology.

The main objective of collecting samples for this study was to examine glaciofluvial materials located over a range of transportation distances from the origin of the cataclastic rocks. It would have been preferable to obtain more information about the particular glacial and sedimentary environments within these two investigated areas but this was not within the scope of the presented work. It is recommended that such a study would enable assessment of the regional effects of glaciofluvial transportation to be made and would help to understand the influence of other regional factors upon the end product of the glaciofluvial material. In outlining our data here, account needs to be taken of the limited number of samples analysed; with the exception of one location, where four samples were collected within the same deposit, only one sample was taken at each location. The different sedimentary units within the various deposits also needs to be taken into consideration when selecting the samples.

The interpretation of the results is based on petrographic examination of the 1-2 mm and 2-4 mm fractions according to the technique described in the experimental section. Hence, the occurrence and contents of cataclastic rocks in the coarser fractions, with regard to the effect of transportation, will not be discussed.

Results from the southeastern Precambrian province show the samples to be dominated by the rock assemblage granites and gneisses. Even though minor fractions of other associated rock-types are observed, all the nine samples examined exhibited a relatively high content of cataclastic rocks, and they appear to be the second most dominant rock assemblage in most of the samples. The cataclastic rocks were all classified as mylonitic rocks, showing fluxion texture with a matrix of microcrystalline and subgranular quartz, and larger porphyroblasts of feldspar. The highest amounts of cataclastic rocks were found in samples close to the mylonite zones, in general agreement with previous observations (Figs. 7 & 8), and the % volume fraction declined with increasing transportation distance from these zones. It is evident from Fig. 7 that the content of cataclastic rocks declines (for both investigated particle sizes) at distances greater then 5 km from the mylonite zone. The maximum content of cataclastic rocks in both fractions is observed to occur at approximately 6 km from the zone.

The sample from location 4 was taken directly above the mylonite zone. In this case, questions might be raised whether the mylonite particles found in this aggregate are derived locally, or if the particles are the result of glaciofluvial transportation from the northern mylonite zone. The low ratio between the content of cataclastic rocks in the 1-2 mm and 2-4 mm fractions indicates, however, that the aggregate is derived locally.

Even though the amount of cataclastic rocks declines with increasing transportation distance, the relatively high contents of such rocks in samples located more remotely and downstream from the mylonite zones, indicate a high 'survival potential' for these rock-types. It is evident from Figs. 5, 7 & 8 that samples close to the mylonite zones contain a relatively higher amount of cataclastic rocks in the 2-4 mm fraction than in the 1-2 mm fraction. This trend is reversed for samples more remote from the major mylonite zones. It appears that cataclastic rocks are dominant in the 2-4 mm fraction in comparison with the 1-2 mm fraction for transportation distances up to about 20 to 25 kilometres downstream from both mylonite zones. For transportation distances greater than 20 to 25 kilometres, cataclastic rocks in the 1-2 mm fraction are more prevalent. The high 'survival potential' of cataclastic rocks could be explained by the observation that such rocks are more durable to mechanical abrasion than most other rock-types (Brattli 1994). Therefore, cataclastic rocks will be able to survive greater transport distances than other rock-types of similar origin without significant erosion of material. Those particles in the 2-4 mm fraction will contribute to the amount

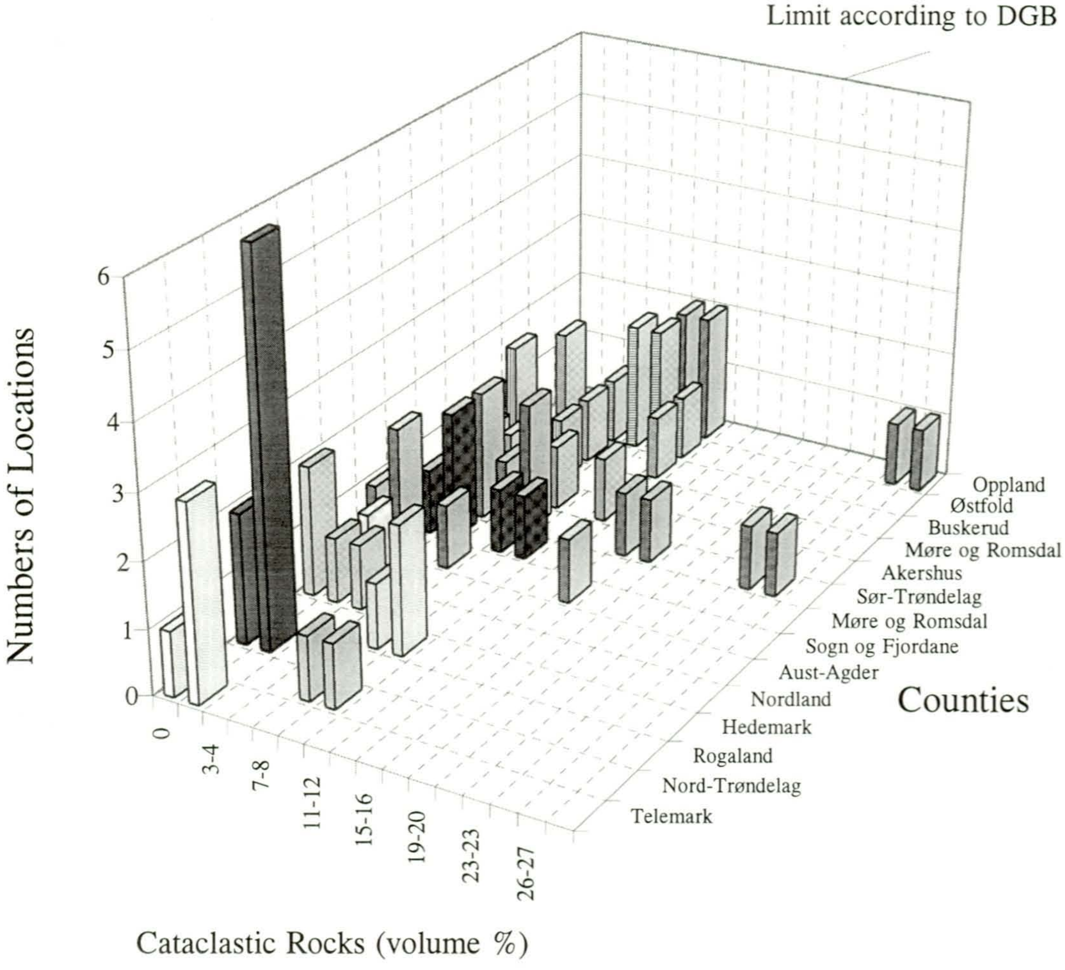

Fig. 4. Distribution of cataclastic rocks in 88 aggregate samples located in different counties in southern Norway; based on petrographic examination at SINTEF Structures and Concrete 1991-1995.

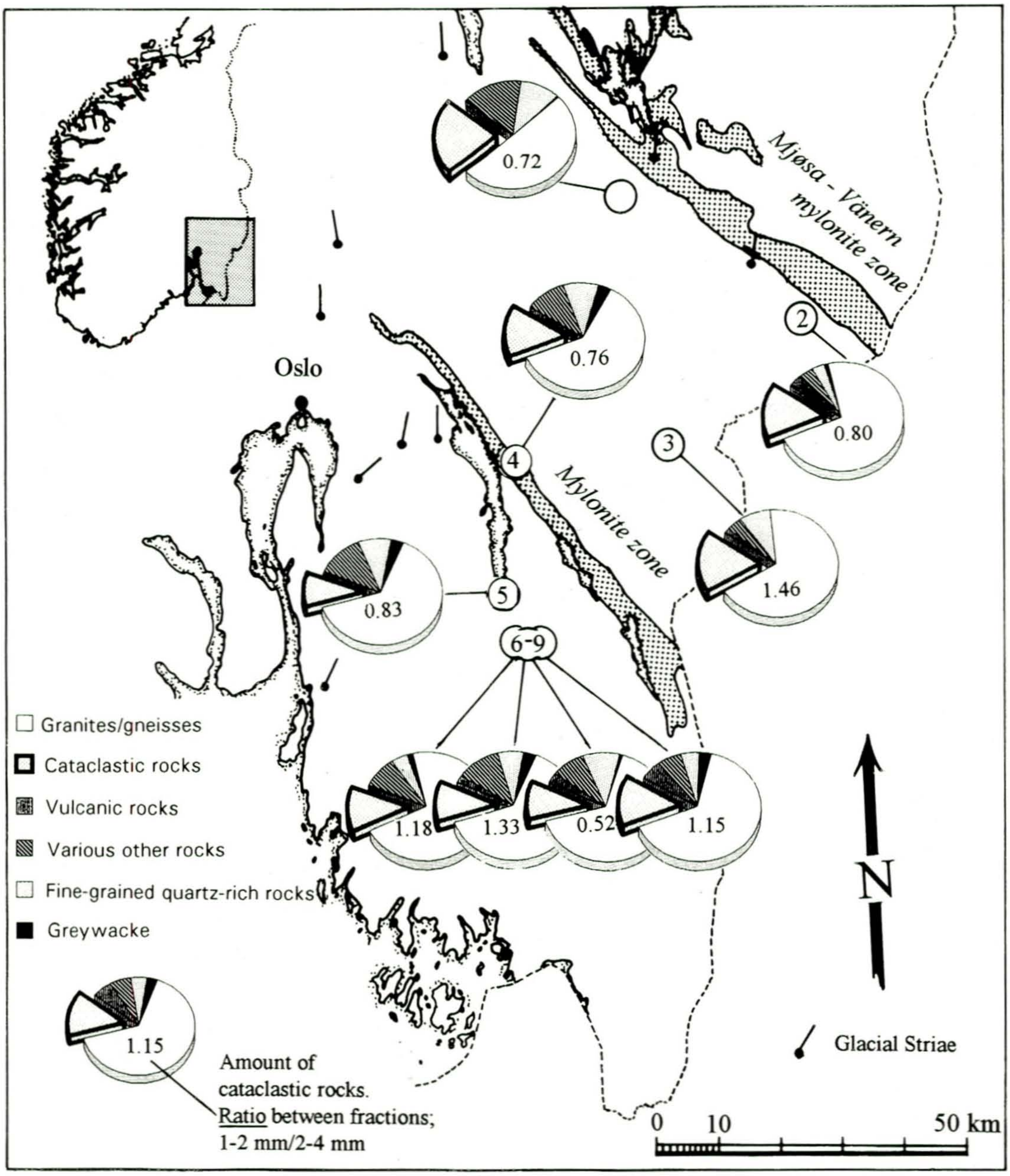

Fig. 5. Sample locations investigated in the southeastern Precambrian province. Graphical presentation of some rock assemblages in the 1-2 mm fraction, and the ratio of cataclastic rocks (1-2 mm/2-4 mm). The main glacial movement in the region has been towards the SSW. (Geological map modified from Sigmond et al. 1984).

of cataclastic rocks in the 1-2 mm fraction, as a result of their undergoing erosion and comminution after travelling long distances.

The four samples (no. 6-9) which were obtained from the same location at Mona demonstrate the homogeneity between different layers within the same glaciofluvial deposit (Fig. 8). No significant differences were observed in the 1-2 mm fraction for samples from the coarse-, fine- and medium-graded layers. However, in the 2-4 mm fraction an unusually high content of cataclastic rocks was found in the medium layer (no.8). No reasons are given for this anomalous result; however, such uncharacteristic behaviour could significantly influence the statistical variation when testing and approving materials for concrete purposes.

Some of the aggregate samples (nos.3 and 6-9) which contained particles of cataclastic rocks were located up to 40 km downstream from their origin in the mylonite zones, in relation to the main ice movement. However, glaciofluvial transportation of materials will not necessarily follow the main ice flow direction, rather it will be governed by local topography. Hence, the true transportation distance for glaciofluvial materials will in most cases be longer than that indicated by the main ice movement.

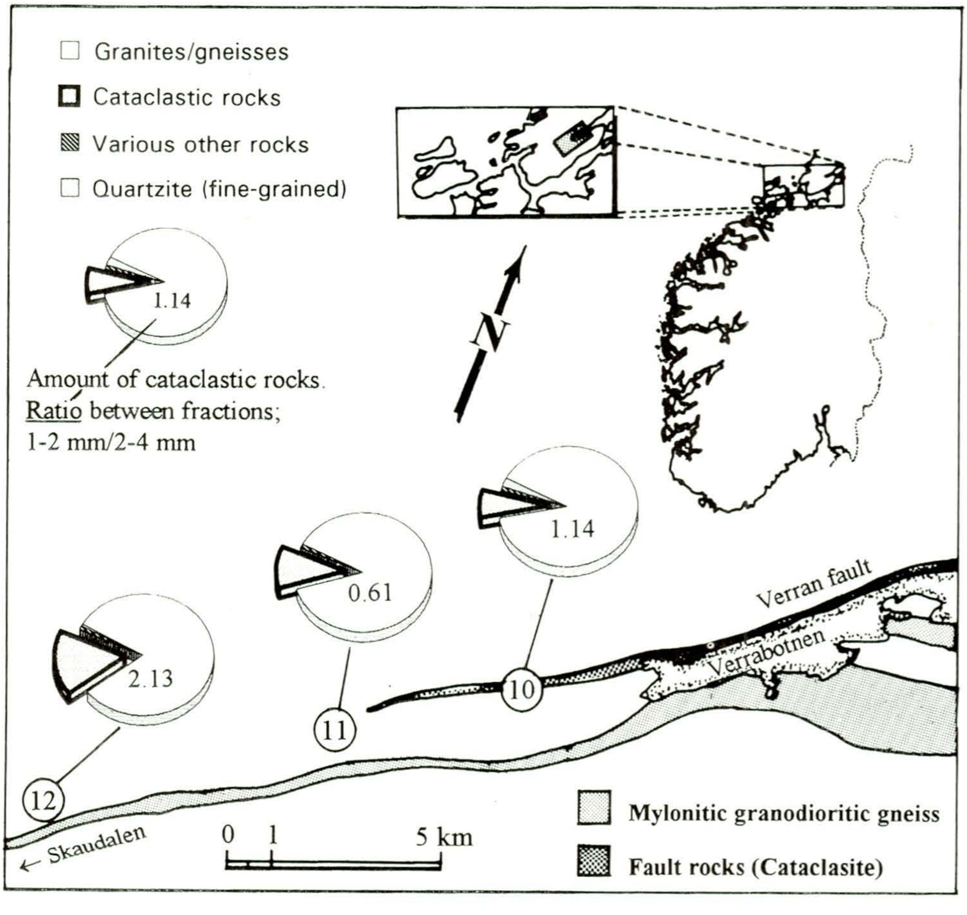

Fig. 6. Sample locations in the investigated area in Verrabotnen. Graphical presentation of some rock assemblages in the 1-2 mm fraction, and the ratio of cataclastic rocks (1-2 mm/2-4 mm). The main glacial movement has been along Verrabotnen, down Skaudalen to the southwest. (Geological map modified from Grønlie et al. 1991).

Table 1. Rock compositions for all twelve tested glaciofluvial samples, given as volume percentages of the 1-2 and 2-4 mm fractions.

Sample	Location	Rock assemblages (%)*											
No.	No.	1	2	3	4	5	6	7	8	9	10	11	12
051094.05, 1-2 mm	1	-	23	-	-	-	-	10	-	1	51	15	-
051094.05, 2-4 mm		-	32	-	-	-	-	13	-	2	49	4	-
051094.02, 1-2 mm	2	-	16	-	-	1	-	3	-	4	72	3	1
051094.02, 2-4 mm		-	20	-	-	1	-	9	-	-	64	6	-
061094.09, 1-2 mm	3	-	19	-	-	-	-	8	-	2	67	4	-
061094.09, 2-4 mm		-	13	-	-	-	-	17	-	6	61	3	-
061094.08, 1-2 mm	4	-	16	-	2	3	-	9	-	-	61	9	-
061094.08, 2-4 mm		-	21	-	-	2	-	13	-	3	50	11	-
061094.05, 1-2 mm	5	-	10	-	3	3	-	9	-	1	64	10	-
061094.05, 2-4 mm		-	12	-	3	4	-	11	-	7	58	5	-
061094.01, 1-2 mm	6	1	13	-	-	2	-	4	-	1	72	7	1
061094.01, 2-4 mm		-	11	-	-	13	-	8	-	5	57	6	-
061094.02, 1-2 mm	7	1	12	-	2	3	-	7	-	2	64	8	1
061094.02, 2-4 mm		3	9	-	-	4	-	9	4	7	59	5	-
061094.03, 1-2 mm	8	1	12	-	2	1	-	9	-	3	66	5	1
061094.03, 2-4 mm		-	23	-	3	7	-	7	-	4	50	6	-
061094.04, 1-2 mm	9	-	15	-	1	3	-	5	-	6	65	5	-
061094.04, 2-4 mm		-	13	-	3	1	-	14	3	6	53	7	-
131094.01, 1-2 mm	10	-	8	-	-	-	-	2	-	-	89	1	-
131094.01, 2-4 mm		-	7	-	-	-	-	-	-	-	91	2	-
131094.02, 1-2 mm	11	-	11	-	-	-	-	-	-	-	88	1	-
131094.02, 2-4 mm		-	18	-	-	-	-	-	-	-	78	4	-
131094.03, 1-2 mm	12	-	17	-	-	-	-	-	-	-	92	-	-
131094.03, 2-4 mm		-	8	-	-	-	-	-	-	-	92	-	-

**Description of the different rock assemblages: 1) sandstones, 2) cataclastic rocks, 3) acid volcanic rocks, 4) argillaceous rocks, 5) greywacke, 6) other rock-types with microcrystalline quartz (e.g. marl), 7) fine grained quartzite, 8) other rock-types containing fine divided quartz (crystal sizes 0.06-0.13 mm), 9) volcanic rocks/gabbro, 10) granites/gneisses, 11) mafic rocks/limestone, 12) other rocks.*

The three samples from Verrabotnen all show a simple mineralogical composition, consisting of only a few rock assemblages. The petrographic examination indicates a dominance of granites and gneisses (Fig. 6), which are the predominant rock-types in the area. The second most frequent rock assemblage is that of cataclastic rocks, in this case classified as cataclasite. The three samples were collected from within a much smaller area than the nine samples from the southeastern Precambrian area.

From Fig. 9, it is evident that for transport distances greater than 7 km downstream from the origin of the fault rock, cataclasite

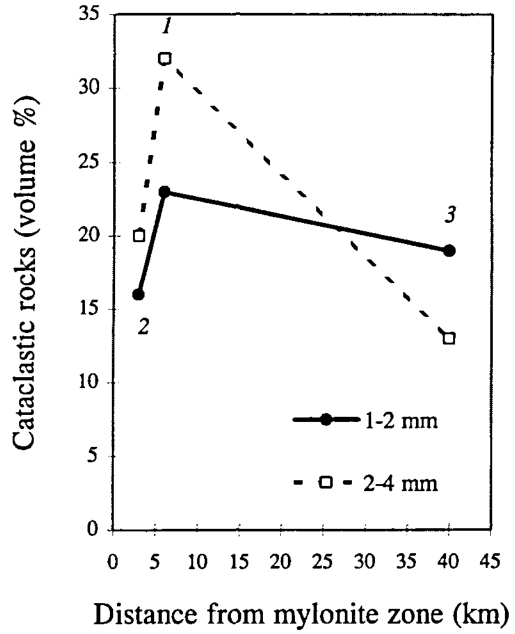

Fig.7. Distribution of mylonitic rocks, in two different fractions, from locations in the southeastern Precambrian province, related to distance (km) from the Mjøsa - Vänern mylonite zone. Numbers (1,2 & 3) represent the locations of the samples.

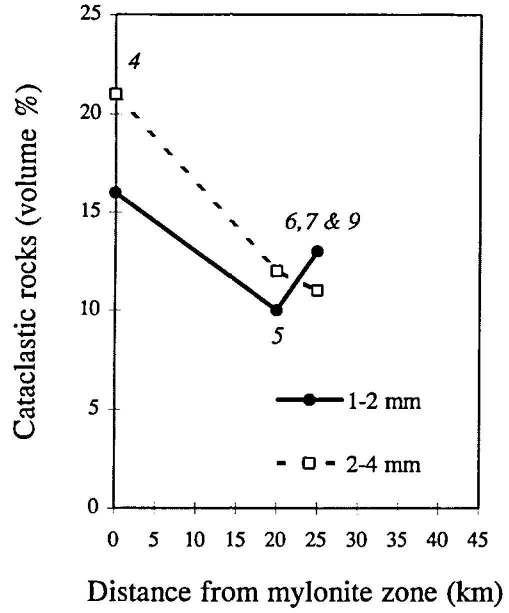

Fig.8. Distribution of mylonitic rocks, in two different fractions in the southeastern Precambrian province related to distance (km) from the second mylonite zone. The numbers (4,5,6,7 &9) represent the different locations of the samples. For locations 6-9, an average values has been applied (no.8). The outlier (No.8) is not included in the graph.

rocks in the 1-2 mm fraction are more abundant than the 2-4 mm fraction. However, the amount of cataclasite in the 2-4 mm fraction reaches its maximum at the second location (no. 11), only 1 km downstream from the origin of the fault rocks, and beyond these distances the volume fraction decreases near the third location (no. 12). In comparison to results analysed for Figs. 7 and 8, the data for Fig. 9 were only from a profile of 10 km. As a consequence of the difference in the area profiled and the difference in the mechanical properties of cataclastic rock-types between the two investigated areas, it is unwise to make any realistic comparison of the trends observed. However, regarding the amount of cataclasite in the 2-4 mm fraction, it appears that the cataclasite shows a lower potential to survive transportation over longer distances, than mylonitic rocks. This is in accordance with the observations of Brattli (1994) who attributed this behaviour to the lower abrasion values for brittle deformed cataclastic rocks (cataclasites) and various granites in comparison to the ductile deformed behaviour of mylonites.

Conclusions

The following main conclusions can be drawn from the present work:

* The results from the data analysis of glaciofluvial materials, even those that were not considered to be representative for Norwegian glaciofluvial sediments, showed that cataclastic rocks are a common constituent in the majority of glaciofluvial sediments. This is in good agreement with the geological bedrock map of southern Norway.

* In some locations cataclastic rocks constitute the major component for all alkali reactive rock-types in the aggregate samples analysed in the present work. Only about 5 % of the investigated samples contained more than 20 % volume fraction of cataclastic rocks. These types of aggregate samples were only observed in the counties of Sør-Trøndelag and Oppland.

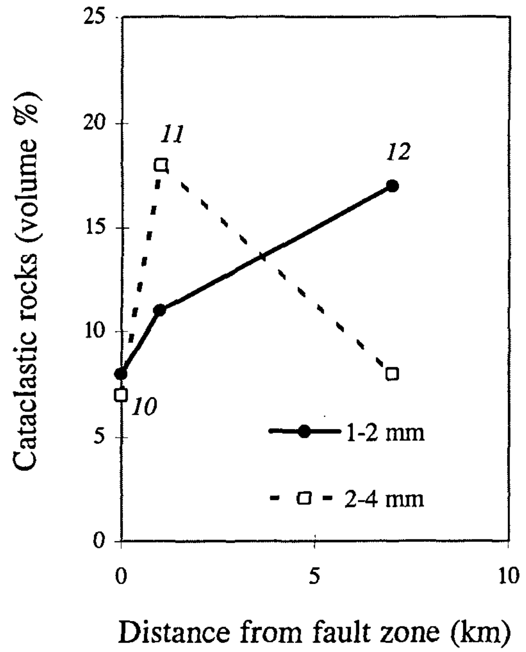

Fig.9. Distribution of cataclastic rocks in two different fractions in the Verrabotnen area related to distance (km) from the fault zone. The numbers (10,11 & 12) represent the different locations of the samples.

* Based on literature studies, both the provenance and the various processes associated with the comminution and transportation of glaciofluvial materials have been identified as the factors which can lead to enhanced amounts of cataclastic rocks occurring in glaciofluvial materials. Examination of glaciofluvial materials, located at various transportation distances from two major mylonite zones, showed relatively high contents of cataclastic rocks, in both the 1-2 mm and the 2-4 mm fractions; whereas glaciofluvial materials near mylonite zones show a higher content of cataclastic rocks in the 2-4 mm fraction than in the 1-2 mm fraction. The opposite trend is observed for samples located further away from the mylonite zones, particularly in the direction of downstream ice movement. In samples taken up to 30-40 km downstream from the parent rock, a high content, or an enrichment of cataclastic rocks (mylonites), was found in the fine fraction (1-2 mm)

* The occurrence of particles of cataclasite in glaciofluvial materials follows similar trends to those described for the mylonite. However, the cataclasite appears to be enriched in the 1-2 mm fraction rather than the 2-4 mm fraction, and occurs much closer to the fault zone than for mylonites. This would seem to indicate that cataclasites are less durable to mechanical abrasion, when transported over such long distances, than mylonitic rocks.

Acknowledgements

The staff at the Department of Geology and Mineral Resources Engineering, University of Trondheim and at the SINTEF Structures and Concrete, are thanked for their technical assistance. The work is a part of the first author's Ph.D. study, which has been funded by the Royal Norwegian Council for Scientific and Industrial Research. He would like to acknowledge the contribution of Dr. S.W. Danielsen and Dr. B. Brattli, for supervision and discussion during the course of the Ph.D study. SINTEF Structures and Concrete is acknowledged for access to their database, and special thanks go to Prof. S. Lippard and Dr. H.H.Patel for their help in the editing and revision of this manuscript.

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Manuscript received April 1995; revised typescript accepted September 1995