Quantifying granular material and deformation: Advantages of combining grain size, shape, and mineral phase recognition analysis

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1. Introduction

Deformation of fault rock material is characterized by the development of a structural fabric or texture, typically having a distinctive grain size and shape distribution. Extensive work has been carried out to understand the physics of fault rocks, including analysis of natural rocks, laboratory experiments, and theoretical modeling (e.g. Abe and Mair, 2005; Allegre et al., 1982; An and Sammis, 1994; Blenkinsop, 1991; Blenkinsop and Fernandes, 2000; Engelder, 1974; Marone and Scholz, 1989; Sammis et al., 1986, 1987; Sammis and Biegel, 1989; Sammis and King, 2007; and many others). However, quantitative studies of fault rock material to date have mainly focused on considering particle size distributions (PSDs). PSDs give valuable information concerning the size characteristics of an ensemble of particles, but say nothing about the shape of the particles i.e. particles having the same PSD do not necessarily show comparable shape characteristics. Particle shape measurements in addition to PSDs may provide a much more effective descriptor of fault rocks and can be easily measured when particle size has been determined. The interplay between particle size and shape influences both the frictional behaviour and porosity and permeability properties of fault zones. However with a few exceptions, notably the recent work by Heilbrunner and Keulen (2006) and Storti et al. (2007), particle shape is often ignored (or at least not quantified) in studies of fault rock material.

Somewhat in contrast, grain shape has been viewed as an important and often used descriptor in qualitative and quantitative sedimentology (e.g. Barrett, 1980; Boggs, 1967; Blott and Pye, 2008; Dobbins and Folk, 1970; Folk, 1955; Howard, 1992; Krumein, 1941; Powers, 1953; Mazzullo and Ritter, 1991; Smith and Cheung, 2005; Wadell, 1936). In this study we show the potential advantages of quantifying PSD, particle shape, and mineralogy for a better understanding of deformation processes.

Textural analysis of fault rock material may yield important constraints on chemical reactions occurring in different mineral phases. Despite the obvious importance of mineralogy, phase differentiation is rarely employed in quantitative studies of fault rock material and instead, the bulk properties of all the fractured material are generally studied together. This is appropriate when...
considering laboratory experiments of mono-mineralogical rocks, where reactions are limited. However, in natural rock when faults and fractures develop and evolve, the system is opened for fluid infiltration. The fluids act as catalysts promoting chemical reactions of specific mineral phases, both as the nucleation of new minerals, and by the growth/decomposition of pre-existing mineral phases (e.g. Antonellini and Aydin, 1994; Chester et al., 1993; Engvik et al., 2005; Morrow et al., 2001; Sibson, 1996; Wintsch et al., 1995).

In this study we use a combination of techniques to highlight characteristic differences and possible different origins of granular material found in fault gouges and clastic dikes, since these features are commonly difficult to distinguish. This includes field observations, classical textural analysis, and the development of a new image analysis technique for quantitative grain characterization.

2. Geological observations

2.1. Geological framework

The rocks studied in this paper are found in the Bremanger Granite Complex (BGC), along the Northwestern contact of the Hornelen basin, the largest of three Devonian basins situated in Western Norway (Fig. 1). These basins are related to the Devonian collapse of the Caledonides and have formed as stepwise coarsening to fining upwards sequences of sand, silt, and conglomerate.

The basins were formed during late- to post-orogenic extension of the overthickened Caledonian crust and reactivation of the Nordfjord-Sogn Detachment Zone mainly due to a relative change in plate motion between Laurentia and Baltica (Osmundsen and Andersen, 2001). Several studies concerning the general basin development and structural geology in the area have been carried out (e.g. Bryhni, 1978; Steel et al., 1985; Norton, 1986; Seranne and Seguret, 1987; Cuthbert, 1991; Hartz et al., 1994; Andersen, 1998; Osmundsen et al., 1998; Osmundsen and Andersen, 2001; Wilks and Cuthbert, 1994 and references therein).

2.2. Field observations

The BGC is exposed on the Bremanger peninsula and is unconformably overlain by Devonian sandstone sediments along its southern border. Previously this contact has been regarded as an angular unconformity (Bryhni, 1978; Steel et al., 1985; Norton, 1986; Seranne and Seguret, 1987; Cuthbert, 1994 and references therein). The rocks studied in this paper are found in the Bremanger Granite Complex (BGC), along the Northwestern contact of the Hornelen basin, the largest of three Devonian basins situated in Western Norway (Fig. 1). These basins are related to the Devonian collapse of the Caledonides and have formed as stepwise coarsening to fining upwards sequences of sand, silt, and conglomerate.

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In the fault sample BRE1505-2 was drilled from the fault zone, with fractures mainly sub-parallel and sub-normal to the fault zone (Fig. 4). Decomposition of plagioclase is strongest near fractures and the plagioclase, epidote and sericite forms a mesh structure surrounding the larger quartz aggregates. The dike wall-rock shown in the thin section consists of 4 large fragments completely surrounded by fractures and the dike itself. We do not find large centimeter sized fragments in the dike material, but we observe granulation within the fractures of the wall-rock.

In the fault sample, the fault zone mainly consists of an “apparently mylonitic” zone and a very fine-grained gouge zone (Fig. 4). The “apparently mylonitic” zone is banded with dark and light coloured bands. The dark bands consist of mainly epidote. The light coloured bands appear as relatively large grains, but under crossed Nicols we observe that they consist of small fragments of mainly quartz and feldspar with minor amounts of epidote. The “apparently mylonitic” zone was not dealt with using the image analysis tool.

In the gouge zone the grain size distribution appears bimodal at this scale of observation, with mainly a fine-grained matrix and few large survivor grains (matrix supported, large matrix/clast ratio). The matrix consists of all the mineral phases found in the wall-rock and minor amounts of accessory minerals (sericite, titanite and zircon) however, the survivor grains are predominantly quartz. The fault zone is cut by thin light coloured bands of mainly quartz and accessory epidote (Fig. 4). Two generations of these bands which displace each other are observed. On the right hand side of the gouge zone there is a thin transition zone with large fragments of the wall-rock breaking loose from the wall (Fig. 4). The fragments encountered and their accumulated displacement is about 60 cm. The locality is located approximately 150 m away from the contact with the basin (see Appendix Detailed geological map for geographical location).

Immediately adjacent to the margin (up to 5 m) the fracturing is locally so intense that a marginal breccia has formed with orthogonal fractures oriented parallel and perpendicular to the basin margin. The perpendicular fractures terminate at the basin margin. Here, no relative shear displacement along the fractures is observed. Near the basin margin (up to 20 m) fractures 2–3 m long and up to 25 cm thick are found. The majority of the fractures are oriented perpendicular to the basin margin (NW–SE to N–S) and are filled with basin and wall-rock material (Bjørk, 2006a). Several of the fractures near the basin margin are in fact pull-apart fractures (Fig. 3). In the fractures we generally observe flow structures, but granulated material with small clasts of wall-rock material is also observed in some subsidiary connecting fractures. Locality BRE39-05 is approximately 20 m from the basin margin (see Appendix Detailed geological map for geographical location).

Two sets of NW–SE oriented fractures filled with brown material exhibiting flow structures are found (Fig. 3) and interpreted as clastic dikes. Dike sample BRE1305A-1 was drilled from the dike shown in Fig. 3.

2.3. Microstructural observations

Samples of the granular material from fault and dike localities described above, were thin sectioned and analyzed using an optical Olympus BX41 microscope and Jeol JSM 6460LV scanning electron microscope. Back scatter electron (BSE)-images with magnifications ranging from 100 to 1500× were taken to study grain size and shape of the fracture infill material. Both thin sections are oriented parallel to strike and perpendicular to the dip directions of the respective fracture structures.

In both samples the wall-rock consists of mainly quartz, plagioclase with radiating epidote needles and K-feldspar, and sericite (Figs. 4 and 6). The wall-rock is intensely fractured in the fault sample, with fractures mainly sub-parallel and sub-normal to the fault zone (Fig. 4). Decomposition of plagioclase is strongest near fractures and the plagioclase, epidote and sericite forms a mesh structure surrounding the larger quartz aggregates. The dike wall-rock shown in the thin section consists of 4 large fragments completely surrounded by fractures and the dike itself. We do not find large centimeter sized fragments in the dike material, but we observe granulation within the fractures of the wall-rock.

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have an elongated shape with their longest axis parallel with the fault in the oriented sections that have been studied. The epidote in the gouge zone displays a complex structure (shown in detail in Fig. 5) that is similar to that of the epidote in the subsidiary fractures in the wall-rock. The epidote grains in the gouge zone are fragmented with irregular shapes, black inclusions of quartz, plagioclase and voids, and zonation with Fe-rich rims. The K-feldspar and plagioclase and quartz grains display an interweaving texture and lobate grain boundaries.

The clastic dike material exists in pull-apart fractures and consists mainly of quartz and epidote of apparently fairly uniform grain size at this scale of observation (Fig. 6). A first order observation is an absence of large “survivor grains”. The abundance of the two different phases in the matrix appears homogenously distributed, however inspection of the dike at low magnifications in the thin section reveals the occurrence of light coloured quartz-rich flow bands. Some granulated material also occurs in subsidiary fractures in the wall-rock of the sample (Fig. 6). Epidote appears to
be much more abundant in the dike than in the gouge sample (Fig. 7). The epidote grains in the dike display a complex structure (Fig. 7). BSE-images reveal that the epidote grains are fragmented with irregular shapes, black inclusions of quartz, plagioclase and voids. Importantly, the epidote grains in this dike sample lack the concentric growth found in the gouge sample.

3. Quantitative method

To extract quantitative particle size and shape information from images of thin sections a new image analysis tool using MATLAB’s Image Processing Toolbox (The MathWorks, 2001) was developed. The program “Gray Scale Image Analysis” (Bjørk, 2006b) uses gray scale-thresholding to separate mineral phases and individual grains. For a more detailed description see Bjørk (2006a) or visit http://folk.uio.no/torbjoeb/image_analysis/. Gray scale BSE-images are read directly into MATLAB. The images are obtained from scanning electron microscope (SEM) studies of the thin sections. The intensity of BSEs is proportional to the atomic mass unit of the element and this phenomenon is used to distinguish the different mineral phases and identify the individual grains (Fig. 8). In this study, three individual mineral phases were differentiated: epidote (E); K-feldspar (K) and plagioclase with quartz (PQ). Sodium-rich plagioclase and quartz have the same intensity range and are difficult to distinguish by this method. It is possible to separate sodium-rich plagioclase and quartz by using the SEM’s EDS-analyzer to map the sodium content, however, this is a very time consuming procedure and therefore is not a feasible tool to use on many images. We therefore treated the two as a single phase, even though we recognize that the rheological properties of the two minerals are somewhat different.

When the appropriate gray scale range is found for a phase of interest, the image is thresholded and turned into a binary image (Fig. 8). Several morphological operations are applied to further separate the individual grains. All morphological operations inspect the pixels in a $3 \times 3$ pixel-environment. First, image noise due to overlapping gray scale intensities of different mineral phases is reduced by removing isolated white pixels. To separate any joined grains, H-bridges and spurs are removed and morphological opening (erosion followed by a dilation) is performed once or several times. Finally, inclusions within the grains are filled. To limit the minimum grain size detectable on each magnification image (i.e. remove matrix), all grains with an area less than 200 pixels are removed. This is a reasonable limit for high resolution images, since smaller matrix thresholds would add error to calculations of particle shape. Grains that touch the edges of the image are removed and their area is subtracted from the total area of the processed image since their entire size and shape are unknown. The image is then labeled using nearest neighbour connectivity with the connecting white pixels (i.e. grains) given a positive integer value while the connecting background remains set to 0. From the resulting labeled image, the size and shape properties (and orientations) of the grains can easily be calculated.

The success of the image processing technique relies predominantly on the contrast and the resolution of the image. If the contrast between particles and matrix, or different phases is small, they will not be properly differentiated. The best results are...
obtained for high resolution images which allow easy phase differentiation and particle separation, and require minimal morphological operations that can alter particle size and shape. Identification of the individual grains is relatively easy when the sample material consists of isolated grains of the same mineral phase or grains with nearly touching boundaries. When grains of the same mineral phase have a long connecting grain boundary, the grain separation becomes more difficult and typically requires more advanced processing. Excessive morphological opening and closing should be avoided, because it imposes the geometric structure of the structuring element onto the particles. Hence, to avoid these unwanted artifacts, prior to processing in MATLAB, the grains of a single mineral phase that have long connected grain boundaries have been separated manually using Adobe Photoshop. Other potential issues include: i) accessory minerals that may be wrongly identified as grains of one of the principal mineral phases and must be removed manually; and ii) overlapping gray scale intensities that will add noise to the image, however this is avoided by the removal of any isolated white pixels and connected pixels smaller than the limit for the minimum grain size detectable.

The main advantage of this method over other image tools is that it is not a “black box method”. The script is written in native
The result. Image analysis is not failsafe, therefore efficient. A key benefit of this tool is that it allows graphical evaluation of however, a vital stage is the user evaluation of the image process-
designed to be semi-automatic and requires minimal user-input,
developed and irregular crystal faces. The zonation is due to different amounts of iron.
quarts, plagioclase and voids, zonation and fragmented appearance with both well
epidote grains in the gouge zone display a complex texture with black inclusions of
class/quartz grains display an interweaving texture and lobate grain boundaries. The
642
BSE-image of the gouge zone in the fault sample. The K-feldspar and plagio-
Fig. 5.
MATLAB which makes it adaptive and user-friendly for non-
graders. In contrast to most available closed-source
programs, the MATLAB script allows full user access to view and
modify the inbuilt functions used to separate phases and identify
grains. This leads to a better understanding of how these operations
affect the resulting particle size and shape. Furthermore, it is very
easy to tune the settings, for various types of images, and statistical
treatment and data visualization are conveniently available in the
same package.
The program “Gray Scale Image Analysis” (Bjørk, 2006b) is
designed to be semi-automatic and requires minimal user-input,
however, a vital stage is the user evaluation of the image process-
ing. A key benefit of this tool is that it allows graphical evaluation of
the result. Image analysis is not failsafe, therefore efficient
evaluation or quality control of the image processing is essential to
check for accurate identification of phases, any misfit of grain
boundaries or any overlap between phases. To evaluate the quality
of the grain identification, the boundaries and centroids of the
identified individual particles are superimposed onto the original
unaltered BSE-image (Fig. 8). Particle overlap, for example, will be
clearly visible when the image of all the phases combined is dis-
played and colour-mapped and can then be manually corrected.
Although, some manual adjustments are inevitable for optimi-
ization of individual images, this image tool can successfully
differentiate different phases and detect individual grains with
minimal user-input. We believe this approach provides a very good
approximation of particle size, shape, and orientation, in a rela-
tively short time, provided that the overlay of detected grain
boundaries match the original image as highlighted above (Fig. 8).

4. Results

We now present quantitative analyses of grain characteristics,
including the relative abundances of different phases, particle size
distributions, and particle shape for the fault gouge and clastic dike
samples using the image analysis method described above.

4.1. Relative abundance of different phases

In the gouge sample, the most abundant mineral phase is plagioclase/quartz (Table 2), both in terms of number of particles
and relative porphyroclast proportion (i.e. area percentage of
particles). Approximately 45% of the particles are plagioclase/
quartz, ~38% are K-feldspar, and only ~17% are epidote. The
porphyroclast proportion for all of the phases combined and the
individual phases varies non-linearly with magnification. The
relative porphyroclast proportion of epidote increases systemati-
cally with higher magnifications.

In the dike sample, plagioclase/quartz is also the most abundant
phase (Table 3). Of the total 948 particles, ~42% are plagioclase/
quartz, ~38% are epidote, and ~20% are K-feldspar. The porphy-
roclast proportion of all the phases combined increases with
magnification. K-feldspar is the least abundant phase at all
magnifications. Plagioclase/quartz dominates at low magnifica-
tions, whereas epidote dominates at high magnifications.

4.2. Particle size distributions

Determining the size of a regular shaped particle, e.g. a sphere, is
simple since it is uniquely defined by its diameter. However, for
cross-sections of irregular shaped particles, size depends on the
way it is defined. The most commonly used measurement of
particle size is equal area diameter, i.e. the diameter of a circle
having the same area as the projected particle (Brittain, 2001). This
is a useful derived measurement since it is a single number that
gets larger or smaller as the particle does and its measurement is
objective and repeatable. Particle size data obtained from image
analysis for the gouge sample and dike sample in this paper are
presented as equal area diameter (unless otherwise stated).

4.2.1. Gouge sample

In the gouge sample, K-feldspar, and plagioclase/quartz have
particles ranging from 2 μm to 190 μm and 410 μm, respectively
(Table 2), whereas epidote only exists as relatively small particles
(between ~2 and ~90 μm). Grain size distributions by number are
presented as cumulative frequency (greater than a given size)
normalized to area and displayed on a log–log plot for a range of
magnifications (Fig. 9). Data are compared for the bulk sample (i.e.
all phases combined) and the individual phases. We suggest that

![Image 38x101 to 279x282](Image 38x548 to 279x727)

Fig. 4. Transmitted light (TL)-image of the fault sample. The wall-rock is highly frag-
menced sub-parallel and sub-normal to the fault. The wall-rock consists of relatively
large aggregates of quartz grains and small grains of plagioclase that have partly or
completely decomposed to epidote and chlorite. Transition zone on the right consists
of relatively large fragments breaking loose from the wall-rock. The gouge material has
a fine-grained matrix and a few large survivor grains. The gouge zone is cut by two
light coloured quartz bands interpreted as “internal faults” formed after the gouge
material had lithified. The “mylonitic” zone on the left is banded with dark (epidote-
rich) and light coloured bands (consisting of small fragments of mainly quartz, feldspar
and minor epidote).

![Image 33x300](Image 33x310)

![Image 33x331](Image 33x352)

![Image 33x373](Image 33x86)

![Image 33x415](Image 33x86)

![Image 33x436](Image 33x86)

![Image 33x456](Image 33x86)

![Image 33x464](Image 33x86)

![Image 33x479](Image 33x86)

![Image 33x482](Image 33x86)

![Image 33x499](Image 33x86)

![Image 33x507](Image 33x86)

![Image 33x516](Image 33x86)

![Image 33x524](Image 33x86)

![Image 33x533](Image 33x86)

![Image 33x540](Image 33x86)

![Image 33x553](Image 33x86)
the data can be fitted reasonably well, for certain size ranges, by a straight line of slope $D$. This indicates that the size distribution approximates a power law with exponent $D$. Note that we now quote a 3-dimensional $D$-value by adding 1 to our 2-dimensional measurement. We employ this standard technique to allow easy comparison of our data to other published work.

The gouge sample has $D$-values of $2.9–3.2$ for the majority of the particle size range (denoted $D_1$) (Table 2 and Fig. 9). For all of the phases combined the $D_1$-value is 2.9977. Similar $D_1$-values and ranges are observed for K-feldspar and plagioclase/quartz. However, in all cases the largest fraction of the particles is best fitted with a larger slope $D_2$ (Table 2 and Fig. 9). Importantly, K-feldspar and plagioclase/quartz phase show similar PSD characteristics which in turn strongly influences the PSD characteristics of all of the phases combined. Unfortunately, this completely masks the PSD characteristics of epidote, the minor phase. Epidote has a higher $D_1$-value of 3.2323 and a relatively small upper grain size limit of $\sim 60 \mu m$ (Fig. 9). In contrast to the other phases, the smallest fraction of epidote grains can be fit with a smaller $D_2$-value of 1.8020. Hence it is crucial to use phase discrimination to get a true PSD evaluation of the minor phase.

4.2.2. Dike sample

Particle size distributions of the dike sample are plotted by number in Fig. 10 and shown in Table 3. The data are reasonably well fitted by a slope with $D$-value of 3.2139 for all phases combined. Plagioclase/quartz has the smallest $D$-value of the individual phases, 2.6673, whereas epidote and K-feldspar have larger $D$-values closer to that of all the phases combined. K-feldspar has a $D$-value of 3.0203 and epidote has a $D$-value of 3.2616. In the dike sample, epidote, and plagioclase/quartz have particles ranging from $0.6 \mu m$ to $100 \mu m$ (Table 2), whereas K-feldspar has an upper particle size boundary of $\sim 65 \mu m$. It is important to note that here the size characteristics of all the phases combined are not particularly representative for the individual mineral phases.

4.3. Particle shape

There are several different ways of quantitatively describing the shape of a particle depending on the aspect of interest. In general it should obey three criteria (Crompton, 2005): (i) It should be intuitive; (ii) it should be normalized to values between zero and 1, thus making interpretation easier; and (iii) it should be sensitive to deviations. It is unlikely that a single shape descriptor can perfectly discriminate and characterize all applications and different combinations of shapes. Hence in this study two different shape parameters, convexity and circularity have been chosen. In the samples analyzed in this study, the orientation of the major axis of grains showed no preferred orientation.

4.3.1. Convexity

Convexity (equivalent to the PARIS factor used by Herwegh et al. (2005)) is a measurement of surface roughness and is calculated by
dividing the convex hull perimeter \((P_{\text{CH}})\) by the actual particle perimeter \((P_{\text{Particle}})\) (equation (1)).

\[
\zeta = \frac{P_{\text{CH}}^2}{P_{\text{Particle}}^2} \tag{1}
\]

The convex hull is the smallest convex polygon that can contain the particle. It is best visualized by the area enclosed by an elastic band stretched around the particle. Convexity has values in the range of 0–1, a smooth particle having convexity equal to 1, whereas an irregular particle has convexity closer to 0 (Fig. 11). The convexity is only affected by surface roughness and is unaffected by overall form and symmetry.

### 4.3.2. Circularity

Circularity is a measure of the ratio of the perimeter of an equal area circle \((P_{\text{EAC}})\) and the perimeter of the actual particle \((P_{\text{Particle}})\) (equation (2)).

\[
\psi = \frac{P_{\text{EAC}}^2}{P_{\text{Particle}}^2} = \frac{4\pi A_{\text{Particle}}}{P_{\text{Particle}}^2} \tag{2}
\]

As the name suggests, circularity is a measure of how close the particle shape is to a circle (Fig. 11). Circularity also has values between 0 and 1, a circle having circularity 1, whereas irregular objects have circularity closer to 0. Circularity is sensitive to both overall shape and symmetry, and surface roughness. In order to optimize the convexity and circularity descriptors for subtle variations in shape, squared terms are used in the numerator and denominator of these descriptors, as shown in equations (1) and (2). The perimeter is calculated as the sum of the Euclidean distance between the boundary pixels and the area is calculated as the number of pixels occupied by the particle. Both perimeter and area are scaled to the appropriate BSE-image scale. Particle shape data are now presented as convexity and circularity versus size for epidote, K-feldspar and, plagioclase/quartz, respectively.

### 4.3.3. Gouge sample

There is a general trend in the gouge sample (observed in all three mineral phases) for a reduction in convexity and circularity with increasing grain size (Fig. 12). This indicates that generally, small grains are smooth and spherical whereas larger grains are rougher and non-circular. Despite the epidote grains being limited to grain smaller \(\sim 100\, \mu m\), a similar shape and size relationship is observed. One subtle difference in phases is that convexity and circularity for epidote are more evenly distributed throughout the range, whereas for K-feldspar and plagioclase/quartz the convexity values are skewed towards the maximum value. Also notable is that K-feldspar and plagioclase/quartz phases contain large particles interpreted to be “survivor grains”.

This subtle difference is also reflected in the convexity characteristics over the entire particle size range (Table 4). The mean values of K-feldspar and plagioclase/quartz are large at approximately \(\sim 0.9\), while epidote has a lower mean value of \(\sim 0.7\). The minimum values are low for all phases (\(\sim 0.2–0.3\)) and the spread is relatively high (\(\sim 0.15–0.20\)). However, the most significant
difference is the skewness and kurtosis. Both K-feldspar and plagioclase/quartz have a long left tails with magnitude $w_j^1:6$ and $w_j^1:6$ and “peaked” distributions ($w_j^5:1$). As opposed to epidote which is more symmetric ($w_j^0:4$) with a lower kurtosis ($w_j^2:1$) giving it a less “peaked” distribution.

We observe the same subtle difference for circularity. K-feldspar and plagioclase/quartz have relatively large mean values ($w_j^0:6$–$w_j^0:65$, respectively) (Table 4). They are left-skewed with relatively a long left tail ($w_j^0:7$–$w_j^0:8$), and the kurtosis is similar to that of a normal distribution ($w_j^3:0$). Epidote has a smaller mean value ($w_j^0:5$), is more symmetric (skewness $w_j^0:10$), and a more “flat” distribution with relatively thin tails (kurtosis $w_j^2:0$). The minimum values are low for all phases ($w_j^0:10$–$w_j^0:15$) and the spread is relatively high ($w_j^0:20$).

4.3.4. Dike sample

The dike sample lacks the presence of “survivor grains” and the upper grain size is limited to $w_j^100$ mm (Fig. 12). The maximum values of both convexity and circularity of all mineral phases decrease with increasing particle size, although the size–shape relationship is less strong than in the gouge sample. Also noticeable

<table>
<thead>
<tr>
<th>Phases</th>
<th>Particle size (diameter $EAC$, $\mu m$</th>
<th>Power-law coefficient, $D$</th>
<th>Range ($\mu m$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Peak</td>
<td>Min.</td>
</tr>
<tr>
<td></td>
<td>$Epidote$</td>
<td>$19.70$</td>
<td>$0.27$</td>
</tr>
<tr>
<td>Small fraction</td>
<td>$1.8020$</td>
<td>$2.26$</td>
<td>$11.57$</td>
</tr>
<tr>
<td>$K$-feldspar</td>
<td>$22.89$</td>
<td>$3.28$</td>
<td>$190.48$</td>
</tr>
<tr>
<td>Large fraction</td>
<td>$4.1209$</td>
<td>$8.97$</td>
<td>$6.48$</td>
</tr>
<tr>
<td>$Plag./quartz$</td>
<td>$42.24$</td>
<td>$3.07$</td>
<td>$410.22$</td>
</tr>
<tr>
<td>Large fraction</td>
<td>$2.8644$</td>
<td>$4.43$</td>
<td>$110.1$</td>
</tr>
<tr>
<td>Combined</td>
<td>$33.05$</td>
<td>$8.01$</td>
<td>$410.22$</td>
</tr>
<tr>
<td>Large fraction</td>
<td>$2.9977$</td>
<td>$3.07$</td>
<td>$115.6$</td>
</tr>
<tr>
<td>$Matrix$</td>
<td>$3.7111$</td>
<td>$29.06$</td>
<td>$254.0$</td>
</tr>
</tbody>
</table>

Table 2

Particle size data from gouge sample BRE1505-2. Porphyroclast proportion and relative porphyroclast proportion are modal area percentage. Small/large fraction is used for the fraction of particles that does not fit the slope $D_j$ for the majority of the particle size range.

<table>
<thead>
<tr>
<th>Magnification</th>
<th>Gouge sample</th>
<th>Number of particles</th>
</tr>
</thead>
<tbody>
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Table 3

Particle size data of the dike sample BRE1305A1. Porphyroclast proportion and relative porphyroclast proportion are modal area percentage. Small/large fraction is used for the fraction of particles that does not fit the slope $D_j$ for the majority of the particle size range.
is that throughout the particle size range, the convexity values of all the phases in the dike sample are skewed towards the maximum value. Whereas for circularity the values are more evenly distributed throughout the particle size range.

Over the entire particle size range, all the individual phases have mean values of ~0.9 for convexity (Table 4). All of the phases are left-skewed, however, epidote and K-feldspar have relatively lower magnitudes of ~1.1, whereas plagioclase/quartz has a larger magnitude of ~1.7. All the distributions are leptokurtic (i.e. kurtosis > 3), but epidote and K-feldspar have relatively small kurtosis values of ~3.6–3.8. Plagioclase/quartz has a large kurtosis value of ~5.7 resulting in a more distinct peak. The minimum values are generally relatively high (compared to the gouge sample) for all phases (~0.3–0.4) and the spread is around 0.12–0.13.

For circularity, the individual phases have similar mean values and spread of ~0.8 ± 0.1 (Table 4). All the phases are left-skewed. Epidote and plagioclase/quartz have skewness of ~0.6 and ~−0.9, respectively, while K-feldspar is slightly more centered around its mean value (skewness ~0.4). Similarly epidote and plagioclase/quartz have kurtosis values of ~2.7 and ~3.0, respectively, close to that of a normal distribution. K-feldspar has a slightly lower kurtosis value of ~2.5. The minimum values are relatively high (compared to the gouge sample) for all phases (~0.4–0.45).

5. Discussion

5.1. Overview

On considering the D-values for the bulk material (i.e. all phases combined) and interpreting consistently with previous work (Marone and Scholz, 1989; Blenkinsop, 1991; An and Sammis, 1994; Blenkinsop and Fernandes, 2000; Storti et al., 2003; Heilbrunner and Keulen, 2006), it would appear that the dike has a more evolved (or mature) size distribution texture than the gouge sample (Tables 2 and 3). The two samples show distinct field and textural characteristics, porphyroclast content, and importantly, the grain size and shape distributions of the individual phases are distinct.

In the gouge sample, K-feldspar and plagioclase/quartz are the main constituents of the porphyroclasts (Table 2). They generally show similar size–shape characteristics (Fig. 13). Epidote, the minor...
porphyroclast constituent shows different characteristics, but importantly, this is masked by the other phases when data for all the phases combined are evaluated.

In contrast, for the dike sample, size and shape characteristics are distinct for different mineral phases. Epidote (more abundant here) and K-feldspar (the least abundant phase) have similar size characteristics in that \( D = 3.0 \) (Table 3). Plagioclase/quartz dominates the porphyroclast assemblage at low magnifications, while epidote is most abundant at high magnifications.

5.2. Insights into fragmentation processes from shape characteristics

In the gouge sample, K-feldspar and plagioclase/quartz show a negative relationship between size and shape, with smaller grains being more circular and smoother which saturates to a value of 1 at small sizes (Fig. 13). Intrgranular fragmentation will create irregular and non-spherical grains, whereas particle abrasion would yield smaller, smooth particles that become progressively more spherical. This may indicate, in our samples, that with increasing granulation and size reduction (presumably associated with increased fault maturity), preferred fracturing along cleavage planes is reduced and the grains are rather abraded or crushed, thus, creating small spherical grains with a smooth surface. Hence, we suggest that both preferential intragranular fragmentation of larger K-feldspar and plagioclase/quartz grains (Blenkinsop, 1991; Blenkinsop and Fernandes, 2000) and particle abrasion (Hattori and Yamamoto, 1999; Storti et al., 2003) have been active during faulting. This apparent switch in deformation mechanism may

![Fig. 10. PSD of the dike sample presented as cumulative frequency (greater than a given size) normalized to area and displayed on a log–log plot for a range of magnifications 100–1500x. The dike has high D-values ranging from ~2.7 to ~3.2 for plagioclase/quartz, K-feldspar, and epidote, respectively. The D-value is ~3.2 for all the phases combined.](image-url)

![Fig. 11. Two different shape parameters, convexity and circularity, have been chosen to discriminate and characterize the particle shapes. Examples of convexity and circularity values for different shapes are illustrated above. Note that convexity is unaffected by overall form and symmetry, while circularity is sensitive to both overall shape and symmetry. Modified from Crompton (2005).](image-url)
explain the D-values larger than 3. This has also been suggested by Storti et al. (2003) and Keulen et al. (2007).

In contrast, the non-diagenetic phases in the dike sample (i.e. those who have not grown from fluid-rock interaction) show an absence of any strong size–shape relationship and in spite of the relatively large D-values, have a distinct lack of the large “survivor grains” typically found in fault gouges (Fig. 13). “Survivor grains” of epidote are absent in both samples, however, this is unsurprising...
Table 4
Table summarizing shape characteristics of samples BRE1505-2 (gouge) and BRE1305A1 (dike). The peak values are taken from the histograms in figure 12.

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<td>−0.91</td>
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Fig. 13. Outlines of convexity, and circularity versus size (equal area diameter) for the individual mineralogical phases in the two samples based on the raw data presented in Fig. 12.
since epidote is a diagenetic mineral that has most likely formed in the dike and gouge samples late in their evolution. Importantly, in the dike sample, we find an absence of any significant fraction of the small irregular and non-spherical grains that are present in the gouge sample (Fig. 13). Instead, the dike has small spherical grains with smooth surfaces indicative of particle abrasion.

5.3. Particle size interpretations

The $D$-values for the gouge sample are generally large, with the majority of the size range fit by $D_1$ (2.9–3.2) and large (or small) particles best fit by $D_2$ (Fig. 9). Higher $D_2$-values are generally observed for the largest particle fraction. Laboratory experiments by Heilbronner and Keulen (2006) and Keulen et al. (2007) show similar results that they interpret as a possible switch in deformation mechanism.

The smallest fraction of epidote is fit by a smaller $D_2$-value of $\sim 1.8$. Although such a $D_2$-value is comparable to that reported from extensional fractures (Marone and Scholz, 1989; Blenkinsop, 1991; Blenkinsop and Fernandes, 2000), in this context it is unlikely that this small fraction is created by a tensile fragmentation process. The low $D_2$-value of epidote might be due to an over-sampling of larger grains (Blenkinsop, 1991) at high magnifications or could represent the grinding limit for epidote (An and Sammis, 1994).

The $D_1$-values we observe in the gouge sample are generally higher than reported from theoretical fragmentation models (Allegre et al., 1982; Turcotte, 1986; Sammis et al., 1986,1987) and from lab experiments and faults in crystalline basement rocks which tend to have $D \sim 2.6$ (Biegel et al., 1989; Marone and Scholz, 1989; Sammis et al., 1986,1987; Sammis and Biegel, 1989), consistent with the constrained fragmentation model of Sammis et al. (1986,1987). However, importantly $D$-values may be influenced by the amount of shear displacement, number of fracturing events and confining pressure (Engelder, 1974; Sammis et al., 1986,1987; Marone and Scholz, 1989; Blenkinsop, 1991; An and Sammis, 1994; Blenkinsop and Fernandes, 2000; Storti et al., 2003).

Our $D_1$-values are comparable to those reported for intensive shear localization in similar cataclastic rocks (adamellite, (gneissic) granodiorite, (gneissic) granites composed mainly of quartz, feldspars, epidote, amphibolite, mica, and chlorite by Blenkinsop (1991); An and Sammis (1994); Heilbronner and Keulen (2006); Keulen et al. (2007). The $D_1$-values are also comparable to other studies carried out on mono-mineralogical rocks by Marone and Scholz (1989); Blenkinsop and Fernandes (2000); Storti et al. (2003) (quartz sand, chromitite, and limestone, respectively). Recent work by Sammis and King (2007) predicts a theoretical $D$-value of 3.0 in high-strain fault gouges. Hence, we suggest in-situ shear granulation is consistent with our PSD observations.

In the dike sample, the data are fit by one single $D$-value. The $D$-values observed are generally larger than those for the gouge sample (Table 3) and are larger than those generally expected for extensional fractures (Marone and Scholz, 1989; Blenkinsop, 1991; Blenkinsop and Fernandes, 2000) or for faults in crystalline basement rocks (Biegel et al., 1989; Marone and Scholz, 1989; Sammis et al., 1986,1987; Sammis and Biegel, 1989). Similarly to the gouge sample, the $D$-values of the dike material are comparable to those reported for intensive shear localization in cataclastic rocks (Marone and Scholz, 1989; Blenkinsop, 1991; An and Sammis, 1994; Blenkinsop and Fernandes, 2000; Storti et al., 2003; Heilbronner and Keulen, 2006; Keulen et al., 2007). If the fracture filling in the dike was solely derived from tensile fracturing of the wall-rock, one would expect substantially larger grain fragments than observed in the gouge sample. Such fragments are clearly not present. In considering a purely sedimentary origin, studies of undeformed sedimentary rocks show that they do not have a fractal PSD, but are often characterized by unimodal, and bimodal PSDs (e.g. Banerjee, 1963; Church, 2003; Ethington, 1977; Ferguson and Tye, 1999; Ferm, 1962). However, these results are not directly applicable to the dike sample in our study since they do not indicate how the transport of basin (i.e. sedimentary) material through a network of fractures may influence the final PSD.

5.4. The effects of mineralogy

It is established that $D$-values larger than 3 can be produced during intensive shear localization in both mono- and poly-mineralogical rocks. Mineralogy may be an important control on dominant deformation mechanism (e.g. fracturing versus abrasion) and the resulting size and shape distributions when the rheological properties and relative proportions of the mineral phases vary.

Blenkinsop (1991) noted that mineralogy is an important factor affecting the PSD of fault rocks. Fault rock collected from the Cajon Pass Drillhole showed systematic variation with increasing plagioclase content. The granite showed the lowest $D$-value, with $D$-values increasing in the granodiorite gneiss, and granodiorite. In the two samples presented in this study, we apparently observe the opposite result where $D$-values increase systematically. Plagioclase/quartz has the lowest value, K-feldspar has an intermediate value, while epidote has the highest value (Tables 2 and 3). This might reflect the rheological properties of the mineral phases, at least for the non-diagenetic phases. However, since plagioclase/quartz is being treated as a single phase a direct comparison may not be appropriate. As noted above, the evaluation of PSDs in relation to mineralogy is an important issue that might help us understand rock fragmentation processes better. To properly address these issues, systematic laboratory deformation experiments on a suit of mineralogically varied samples with evaluation of size and shape characteristics of the individual deformed mineral phases would be essential.

Few quantitative studies of fault rock shape characteristics exist to date, however we note that Heilbronner and Keulen (2006) and Storti et al. (2007) have conducted particle shape analyses of fault rock material. The shape analyses by Heilbronner and Keulen (2006) are not easily comparable to the shape descriptors used in this study. Storti et al. (2007) measured angularity from fault cores in limestone. Their definition of angularity ($a = P/P_A$ where $P$ and $P_A$ are the perimeter and area, respectively) is in fact comparable to our definition of circularity $\psi = 4\pi a/A$, where we see that the circularity is proportional to $1/a$. We suggest that the term angularity may not be optimal since this shape factor describes how close a particle’s shape is to that of a circle? For example, two rectangles with different aspect ratios will qualitatively have an angular shape, but different angularity values. After clarifying these terminological distinctions, the results presented in this paper appear to be opposite to the conclusions of Storti et al. (2007). However, it is important to note the significant differences in rock type and particle size range in the respective studies. In our study we have examined fracture material in granodiorite with a particle size range of 2.21–410.22 mm, while Storti et al. (2007) have studied fracture material in limestone (mostly calcite with sub-ordered dolomite) with a particle size classes between 0.125 mm and 1.00 mm.

5.5. Field and textural observations

Both field and textural observations support in-situ granulation in the gouge sample. The relatively low apparent displacement observed in (Fig. 2) combined with the relatively high $D_1$-values may be reconciled by high confining pressure and/or several faulting events, involving both sinistral and dextral movement.
Repeated faulting events might be represented by the internal shear bands in the fault gouge (Fig. 4). Another possibility is that the apparent displacement observed in the field is much smaller than the actual shear displacement. We also observe fragmentation of wall-rock material (Fig. 4) consistent with in-situ granulation.

It is difficult to distinguish between wall-rock material and basin material, in the dike sample, on the basis of chemical analysis since the clasts in the Hornelen basin are lithologically identical to the rocks of the BGC (Cuthbert, 1991). However, field and textural observations can give an indication of the origin of the dike material. From the field observations it is clear that the dike is a pull-apart fracture (Fig. 3). The dikes are also connected to sub-parallel fractures with granulated material. These fractures have the same orientation (160/70, 154/72) as the fractures and faults found elsewhere in the granodiorite and in the basin (Bjork, 2006a) and it is reasonable to assume that they are related to the basin development.

The material in the pull-apart dike has three possible origins. It is either: (i) granulated material of the wall-rock that has been transported from the connecting fractures; (ii) material derived from the basin; or (iii) a combination of both. We observe relatively large grains locally (Fig. 3). However, we also observe minor granulation in fractures connected to the dike itself (Fig. 3) and in the wall-rock of the dike sample (Fig. 6). The absence of large grains may suggest that the majority of the granulation was not in-situ, but occurred in the connecting fractures and the material was then transported into the pull-apart fractures. Since the fractures and granulation zone are thin and/or under compressive stress, transport of relatively large grains to the tensile fractures (low pressure zones) would be inhibited. At the same time, we observe flow structures in the field (Fig. 3). This is not direct evidence of basin infill, only that a pressurized fluid was present. However, the proximity to the basin margin means that infill of basin material is not unreasonable.

The field and textural observations, and particle size and shape characteristics in the dike sample show a mixed signature. Hence, we suggest the dike material has been derived from both granulation in subsidiary fractures and infill from the basin.

5.6. Coupled reaction–deformation processes

An important point, often neglected in particle analyses of fault material is the effect of mineralogy and dynamics of coupled deformation–reaction processes. In both samples, observations suggest that several minerals form during and/or after deformation in addition to epidote. Chlorite appears to be related to the faulting event since it increases in the wall-rock towards the fault gouge sample. Sericite is also found in the fracture material in both samples. These minerals are hydrous and indicate fluid transport in both samples. The role of fluids is clearly important. The mineral growth of epidote will influence both the size and shape of the grains, and treating them as non-reactant clasts that become granulated is somewhat naive.

In the gouge sample the epidote grains are zoned with iron-rich outer parts that display a complex shape, both in the wall-rock and in the gouge (Fig. 5). The shape is partly euhedral and partly irregular suggesting that the outer parts grew after cataclasisation. This is strong evidence of cataclastic deformation and this implies fluid presence in the fault zone and several deformation events, otherwise there would be no reason for the epidote to grow.

The epidote in the dike sample has a comparable texture to the gouge sample, with the exception that it shows no evidence of concentric growth (Fig. 7). This does not exclude epidote growth in the connecting fractures during cataclasisation, but documents that the iron-content in the fluid was comparable before and after any cataclasism. It is not unreasonable to infer that the proximity to the basin allows for substantial fluid infiltration that could buffer the iron-content in the fractures close to the basin margin. However, this buffering would be unlikely in faults and fractures, e.g. the gouge sample, ~150 m away from the basin margin. This distinction could potentially account for the differing modal percentage of epidote in the two samples. The lack of irregular epidote grains in the dike might indicate that the deformation has not involved sequential faulting events and/or that stress state of the system has favoured abrasion as the dominant deformation mechanism.

6. Conclusions

Granular material from a fault and a clastic dike in granodiorite at the NW contact zone of the Hornelen basin have been compared by a new digital image analysis tool to extract size and shape characteristics for individual mineral phases. We demonstrate the importance of incorporating both field and textural observations and the advantage of combining grain size and shape analysis with mineral phase recognition. Our results reveal quantifiable differences in the granular material. Hence a distinct origin of these materials is interpreted.

Particle size distributions measured in both samples are consistent with shear fracturing ($D \sim 3.0–3.2$). However, the shape characteristics of the two samples are distinct. The granular material from the dike shows no clear shape–size relationship. In contrast, the non-diagenetic phases in the gouge show a systematic shape–size relationship (smaller grains being circular and smoother) suggesting a shift in dominant deformation mechanism from intragranular fracturing to abrasion with decreasing grain size. This apparent change in deformation mechanism may explain the $D$-values larger than 3. Similarly, field observations, petrography, and the shape and texture of epidote indicate that this granular material was formed by repeated faulting events.

Field and textural observations, combined with grain size and shape characteristics indicate that the dike sample has a mixed origin. Granulation in fractures connecting to the dike indicates mechanical deformation, while flow structures, texture, grain shape, and high content of epidote, as well as the presence of other hydrous minerals in the dike itself suggest that fluids from the basin have been present. Hence, we suggest that the dike material is partly derived from granulation in connecting fractures and partly from infill of basin material due to the proximity to the basin margin.

Our results highlight the importance and added value of a combined approach incorporating phase recognition, grain size and shape analysis in granular materials. We demonstrate that particle shape measurements in addition to PSDs provide a much more effective descriptor of fault rocks. An important future step will be to adopt a standardized set of shape descriptors so different studies can be effectively and systematically compared.

The results also show that phase differentiation is extremely important. Mineralogy may control the dominant deformation mechanism and it is evident that without phase differentiation, subtle signals in PSD, and shape characteristics would not be recognized, and the bulk signal is potentially unrepresentative, particularly for the least abundant phase.

Acknowledgements

We wish to thank the reviewers, especially Andrea Billi, whose comments helped improve the manuscript. This work was financed by the Centre of Excellence for Physics of Geological Processes at the University of Oslo.
Appendix. Detailed geological map

Detailed geological map of the field area (61°47'27.07"N 4°59'55.64"E).

References


