STRESS ANALYSIS OF DEEPLY ERODED ANALOGS OF THE SAN ANDREAS FAULT (A RENEWAL)

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Introduction

We have studied deformation-induced microstructures in quartzo-feldspathic rocks from the Nordre Stromfjord shear zone, within the central part of the Nagssugtoqidian mobile belt of West Greenland (Figure 1).

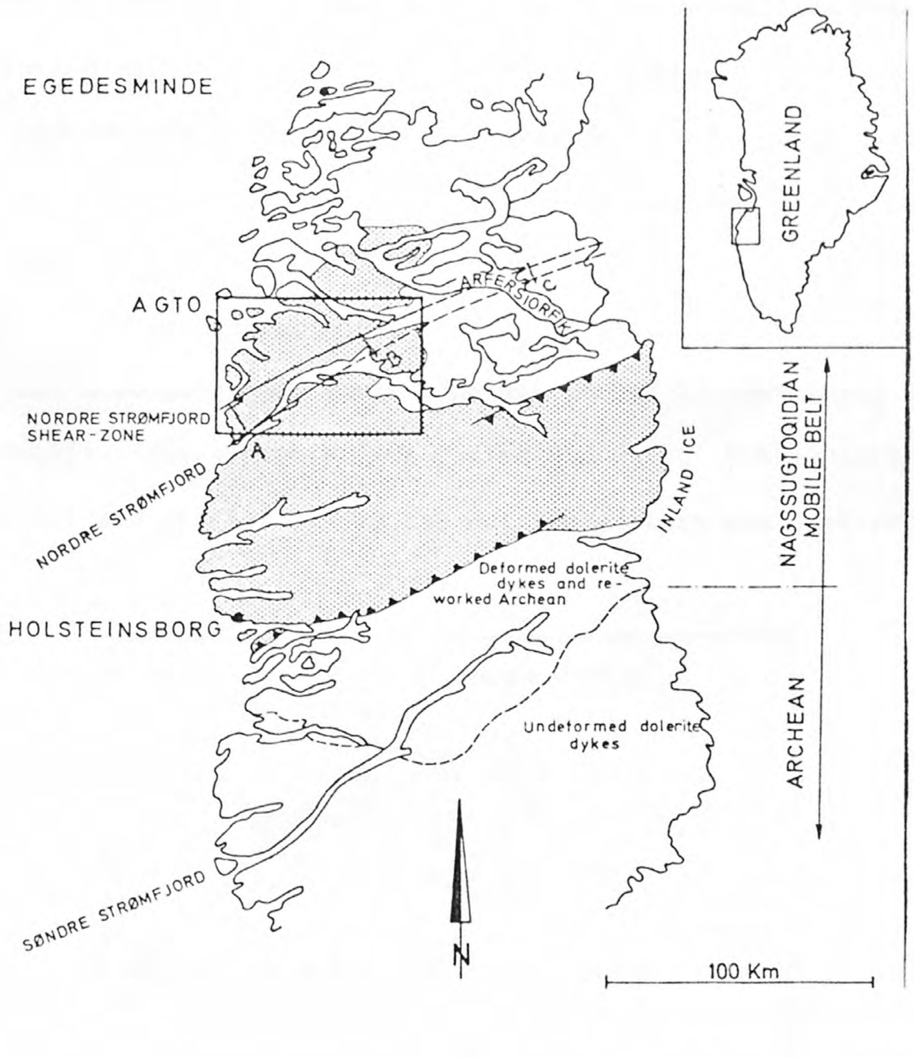

Figure 1. The location of the Nordre Stromfjord shear zone in the Nagssugtoqidian mobile belt of West Greenland. The shaded area is the granulite facies Isortoq complex, which is bounded to the south and north by amphibolite facies area - the Ikertoq and Egedesminde complexes, respectively. The Agto map sheet has been mapped in detail by personnel of the Dept. of Geology, Aarhus University, Denmark. The lines A, B, and C indicate the location of measured sections that we are studying in this project. Map from Bak et al. (1975).

The shear zone extends from the mouth of Nordre Stromfjord in an ENE direction towards the inland ice, a distance of 150 km. The width of the zone decreases from approximately 15 km at the coast to approximately 6 km at the ice. Approximately halfway between the coast and the ice the shear zone crosses a regional granulite facies/amphibolite facies boundary (Figure 1), which apparently is not of tectonic origin. A fanning of the structures has been found; the foliation dips steeply NNW at the northern boundary of the zone, is vertical in the central part, and dips steeply SSE at the southern boundary. The variation in width of the zone, the fact that it cuts the granulite facies/amphibolite facies boundary, and the fanning of the structures has led to a model for the structural evolution of the area. Bak et al. (1975) have proposed that a wedge-shaped shear zone was formed in the crust, cutting the granulite facies/amphibolite facies boundary. Subsequently, differential uplift and erosion led to the outcrop pattern now observed (Figure 2).

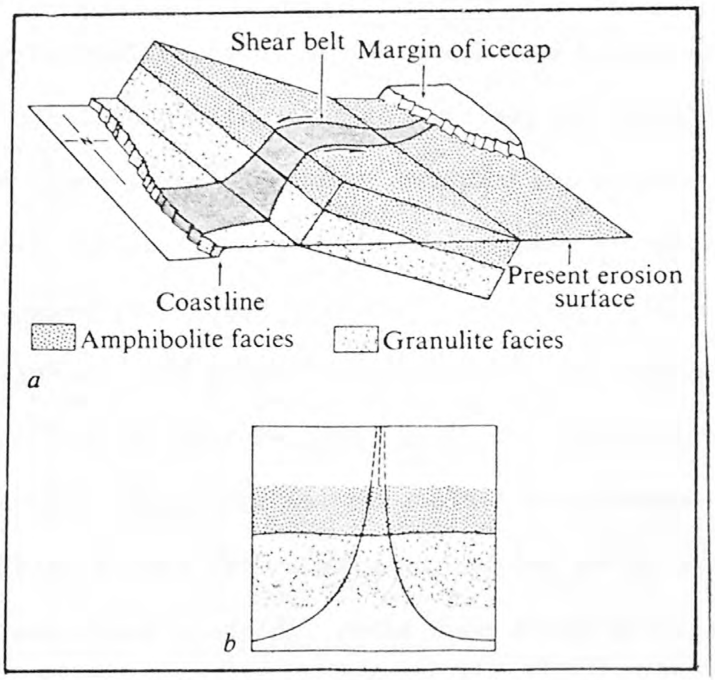

Figure 2. Model for the structural evolution of the Nordre Stromfjord area. In Figure 2b, the inferred wedge-shape of the zone is shown. In Figure 2a, the present outcrop pattern which could be a result of differential uplift and erosion is shown. (from Bak et al. 1975).

According to this model, rocks which were originally deformed at successively higher levels in the crust are now exposed from west to east. Thus, this zone seems to offer a unique opportunity to study rocks which were deformed in the same deformational episode, but at different depths in the crust - that is, under different physical conditions (temperature, lithostatic pressure, and possibly, with H_2O and other volatiles).

Our work on rocks from the shear zone has concentrated on two projects: 1) A study of the microstructures of the rocks and an attempt to apply the paleopiezometers - free dislocation density, subgrain size and dynamically recrystallized grain size - to determine the stress level during the formation of the shear zone; and 2) A study of crystal defects in plagioclase feldspars from the shear zone.

1. Microstructures and paleopiezometers

The dominant rocks in the area are biotite gneisses of tonalitic to granodioritic composition. The principal minerals are plagioclase (An_{25-40}), quartz, alkali feldspar, biotite, and, in the granulite facies area, orthopyroxene. Other rock types include charnockite, granitic gneiss, and hornblende gneiss of dioritic to tonalitic composition. Rocks of sedimentary origin occur as conformable bands and layers within the gneisses. These metasedimentary rocks have a wide range of composition, mineralogy, and texture, from garnet biotite sillimanite gneisses to rusty, sulphide- and graphite-bearing schists, marbles and calc-silicate rocks, often interlayered with pyroxene amphibolites.

In order to determine whether or not we could find systematic variations in microstructures and/or stress levels between various parts of the shear zone, we have studied, and are still studying, rocks from three different measured sections across the shear zone (Figure 1): section A in the westernmost part of the granulite facies area of the zone, section B close to the granulite facies/amphibolite facies boundary, and section C in the eastern part of the amphibolite facies area of the zone. Within each of these sections, the microstructures of the quartzo-feldspathic rocks vary somewhat locally, presumably due to local variations in stress and/or strain, and/or content of H_2O. A more general microstructural variation is apparent, going from west to east in the shear zone, that is, from the granulite facies part of the zone to the amphibolite facies part of the shear zone.

In rocks from the westernmost part of the shear zone, microstructures typical of strongly deformed rocks, which have not undergone significant post-deformational annealing, are commonly observed. Quartz grains have a strong preferred habit orientation and irregular grain boundaries. Undulatory extinction, deformation bands, and subgrains are abundant. Feldspar grains are moderately elongated, usually not as much as the quartz grains, and their grain boundaries are somewhat sutured. Most feldspar grains have undulatory extinction with local development of deformation bands and subgrains. The alkali feldspars show cross-hatch twin patterns and in the plagioclase most twins are discontinuous. In many samples the grain size distribution is clearly bimodal. Relict grains of quartz and feldspar are 0.5 to 2.0 mm across and have recrystallized to a grain size of 20-40 microns along grain and subgrain boundaries. Up to 30% of the rocks are recrystallized. Recrystallized quartz grains are commonly elongated and show deformation-induced intracrystalline structures, suggesting that the recrystallization was dynamic. Amphiboles and pyroxenes in the gneisses have a strong preferred habit and lattice orientation but, apart from slight undulatory extinction, do not show much evidence of deformation.

Eastward into the shear zone, deformational effects become less apparent in the microstructures of the rocks. The grains become more equant, grain boundaries are smoother, and in rocks from the amphibolite facies area, bimodal grain size distributions are no longer observed. This microstructural variation could be due to a variation in shear strain and, perhaps, stress. However, if we make the reasonable assumption that the offset across the zone is constant or near-constant, irrespective of width, shear strain must have been higher in the eastern part of the zone than in the western part. Thus, we would expect the rocks in the amphibolite facies area to show the strongest effects of deformation. This is the reverse trend of what we have found. A plausible explanation for the observed microstructural variation is that the rocks in the amphibolite facies area have undergone a much more extensive post-deformational annealing than the rocks in the granulite facies area, possibly due to a higher content of H_2O in the amphibolite facies rocks.

We have studied the microstructures of quartz, plagioclase, and a few hornblende grains, from quartzo-feldspathic gneisses from the shear zone, by optical and electron microscopy. The hornblendes showed a very low density of free dislocations ($<10^7$ free dislocations/cm^2). The hornblendes do show a very strong habit and lattice preferred orientation, suggesting that they did not recrystallize post-tectonically. The very low density of free dislocations suggests that this preferred orientation is not entirely due to intracrystalline slip. The hornblendes are much "stronger" minerals than quartz and feldspar and, therefore, we suggest that the preferred orientation is mainly due to passive rotation of the hornblende grains in a deforming matrix of quartz and feldspar.

We have made a detailed transmission electron microscope investigation of defects in the plagioclase feldspars, and have considered the possibility of using microstructural data from the plagioclases as a paleopiezometer. Many quartzo-felspathic rocks can be viewed as being built-up of a stress-supporting framework of feldspars with grains of quartz and other minerals situated in interstices in the framework. It may thus be more appropriate to use microstructural data from feldspars rather than from quartz when trying to apply paleopiezometers to quartzo-feldspathic rocks. In quartz the free dislocation density usually varies up to a factor of 2 between grains in the same thin-section, but in plagioclase we have found variations up to a factor of 15, which makes it impossible to correlate stress with the density of free dislocations in plagioclase. As will be discussed later, plastic deformation of plagioclases is very heterogeneous, and the amount of strain by intra-crystalline slip that individual plagioclase grains undergo is dependent on their orientation in the stress field. We have studied plagioclase only from granulite facies rocks, and these show development of dislocation boundaries and subgrains, though not as extensively as in quartz. This observation is important in the evaluation of the physical conditions during the deformation, using the assumption that at least some of these structures were formed syn-tectonically. White (1975) has shown that dislocation boundaries and subgrains in plagioclase form only during deformation at high amphibolite facies or higher metamorphic conditions. The reason for this is that the plagioclases at lower temperatures have a superstructure within which dislocation climb is very limited. However, at temperatures corresponding to high amphibolite facies, this superstructure breaks down partially, making dislocation climb and the formation of boundaries and subgrains possible. The widespread occurrence of boundaries and subgrains in these plagioclases suggest that a major part of the deformation leading to the formation of the shear zone occurred at the highest metamorphic conditions in the area, though we can not exclude the possibility that deformation continued during decreasing metamorphic temperatures.

Because we can not use microstructural data from the plagioclases to assess the stress level during the formation of the shear zone, we have undertaken a quantitative study of microstructures in quartz. We have measured the free dislocation density in 6 samples from section A of the shear zone (Fig. 1), in 13 samples from section B, and in 10 samples from section C. In quartz grains from section A we have found free dislocation densities of 5-10 x $10^8 cm^{-2}$, in grains from section B, densities of 1-5 x $10^8 cm^{-2}$, and in grains from section C, densities of 3.5-8 x $10^8 cm^{-2}$. These free dislocation densities correspond to stresses of 1.5-2.0 kbar, 0.7-1.5 kbar, and 1.2-1.9 kbar, respectively. We have not found any systematic variations in density across the shear zone and no difference in density between samples from the zone and from the region outside the shear zone. Thus, these results indicate that there has been no stress concentration in the shear zone and that there is a stress minimum at the granulite facies/amphibolite facies boundary. From experiments it is known that the density of free dislocations is easily changed by post-deformational annealing or by a later deformation event at another stress level. It may be that the densities of free dislocations in samples from this shear zone have changed after the main deformational event, and the stress-values obtained from them might not be representative of the stress during formation of the shear zone.

To test this possibility we are presently undertaking a study of subgrain sizes in quartz-bearing samples collected from the shear zone. We have measured subgrain sizes in samples from sections A and B. In grains from section A the average subgrain size has been found to be 4 microns, corresponding to a differential stress of 0.5 kbar; in quartz grains from section B the average subgrain size of 5 microns corresponds to a stress of 0.4 kbar. In section B we have also studied subgrain sizes in samples from outside the shear zone and found an average size of 10 microns, corresponding to a stress of 0.2 kbar. There is clearly a discrepency between the results obtained from dislocation densities and subgrain sizes. We consider the subgrains to provide a more reliable stress estimate than the dislocation densities, which presumably have been changed by a late, high-stress deformational event.

We are reluctant to use sizes of dynamically recrystallized grains to estimate the stresses in this example because the size of recrystallized quartz grains in quartzo-feldspathic rocks is influenced by the presence of other mineral phases. Furthermore, recent experimental results indicate that the size of recrystallized grains depends on the process by which they are formed (Guillope and Poirier, 1979) and may be dependent on water-content in the rock (Etheridge and Wilkie, 1979).

2. Crystal defects in plagioclase from the Nordre Stromfjord shear zone

As previously mentioned, many crustal rocks can be considered to be built up of a stress-supporting framework of feldspars with quartz and other minerals situated in interstices. In order to acquire more knowledge on the rheology of these rocks it is necessary to obtain more information on the deformational properties and defect types in the feldspars. This information may be obtained from experimental deformation of feldspars and from microstructural studies of naturally deformed rocks. There has been relatively little work done on deformation-induced microstructures in the feldspars compared to other important minerals such as quartz, calcite, and olivine. Transmission electron microscopy on feldspars is fairly complicated due to their low symmetry (triclinic - monoclinic), their complex structure, and the effects of elastic anisotropy.

Plagioclases in gneisses from the granulite facies part of the shear zone provide good examples of microstructures which formed during natural deformation at high temperature and confining pressure. We are undertaking a study of dislocations in these plagioclases in order to identify the most important types of dislocations and to make inferences about slip-systems and deformational properties.

In the electron microscope, Burger's vectors are usually identified by applying the invisibility criteria $\bar{g}\cdot\bar{b} = 0$, $\bar{g}.\bar{b}_e = 0$, and $\bar{g}\cdot(\bar{b} \times \bar{u}) = 0$

($\bar{g}$ is the diffracting vector, $\bar{b}$ is the Burger's vector, $\bar{b}_e$ is the edge-component of the Burger's vector, and $\bar{u}$ is a unit vector along the dislocation line). When these conditions are satisfied, the lattice diffracts the electron beam as though it were perfect, and the dislocation will be invisible. By finding two or more such conditions of invisibility, the Burger's vector can be identified. These conditions are very restrictive. They can be satisfied for a number of diffracting vectors for pure screw dislocations, but only for one diffracting vector for edge dislocations and they can not be satisfied for mixed dislocations. Furthermore, the invisibility criteria are based on the theory of linear elastic isotropy and they can only be applied to a limited extent to elastically anisotropic materials such as feldspars. In elastically anisotropic materials, many dislocations show a contrast even though the invisibility criteria are satisfied. To overcome these problems we have made computer programs which can make theoretical micrographs of perfect and dissociated dislocations in feldspars so that we can identify the dislocations by the image-matching technique (Head et al., 1973). This technique is based on the fact that the contrast from a given dislocation in a given diffracting condition depends on the orientation and magnitude of its Burger's vector. Thus, after having taken a micrograph of a given dislocation, we can make theoretical micrographs for all possible Burger's vectors in feldspars, and in the same diffracting condition as the transmission electron micrograph. We can then identify the Burger's vector by finding the theoretical micrograph which matches the transmission electron micrograph. By applying this technique, we have identified the most important types of dislocations in the plagioclases.

The density of free dislocations in the plagioclases is very variable. In grains with a high free dislocation density, the microstructure is dominated by one set of straight dislocations; often more than 90% of the dislocations present in these samples belong to this set. In samples with lower densities, there seems to be a greater diversity in dislocation types. We have identified the Burger's vector of these dominant dislocations as being [001], which is the shortest Burger's vector in the plagioclases. Most of these dislocations, which commonly occur in dipole pairs, are in a pure screw orientation. On the basis of weak-beam microscopy and the image-matching technique, we have found that these dislocations are dissociated in the (010)-plane according to the reaction [001] = ½[001] + ½[001]. The two partials are about 200Å apart.

The [001] screw dislocation is the most important type of dislocation in the plagioclases. Of the remaining types, dislocations with Burger's vectors $\bar{b}$ = ½[001] and $\bar{b}$ = ½[1$\bar{1}$0] seem to be the most common. Dislocations with these Burger's vectors are in pure screw orientation or are mixed dislocations with line-directions <uv0> or have line directions close to the [101] direction. These dislocations are also found to be dissociated, the two partials being 150 to 200Å apart. We are presently trying to determine the dissociation reaction of these Burger's vectors. only other Burger's vector we have found is $\bar{b}$ = ½[112], which is associated with line directions close to [101]. These dislocations also seem to be dissociated, but we have not yet determined the dissociation reaction.

Our study is not yet completed, but the results obtained so far suggest the following conclusions:

1. There seems to be a relatively large number of dislocation types in the plagioclases, but only a few are quantitatively important. Dislocations with the Burger's vector $\bar{b}$ = [001] are strongly dominating.

2. A great deal of caution should be taken in inferring slip systems from dislocation types because the dislocations may have climbed or cross-slipped. However, our study does give an indication of what the most important slip systems might be. The slip planes of dislocations with Burger's vector [001]

are of the type {hk0} and the (010)-plane is possibly the most important of these. The [001] screw dislocations seem to be dissociated in the (010) plane; this may be a slip-plane dissociation. Earlier studies also indicate that (010) is the most important slip-plane in feldspars. It was the only slip plane found by Borg and Heard (1970) in their experimental deformation of plagioclase. This slip plane has also been inferred from optical microscopy studies of kink bands in naturally deformed plagioclases (Seifert, 1965).

Dislocations with Burger's vectors ½[110] and ½[110] often have line directions of the type <uv0>, indicating that (001) is the slip plane of these dislocations. Slip planes of screw dislocations parallel to [110] or $[1\bar{1}0]$ could also be of the type (hhl), where h is non-zero. The slip planes of dislocations with line directions close to 101 and Burger's vectors ½[110], ½$[1\bar{1}0]$, or ½[112] are presumably of the type (hhl).

3. The great variation in free dislocation densities and the dominance of the Burger's vector [001] (possibly primarily associated the the slip plane (010)) suggests that plastic deformation by intracrystalline slip is very heterogeneous in feldspars. The activation energy associated with the slip system (010)[001] may be much smaller than that associated with other systems. The amount of strain, by intracrystalline slip, that an individual plagioclase grain will undergo is dependent on the orientation of its (010) [001] slip system in the stress field.

4. It appears that most, if not all, dislocations in the plagioclases are dissociated. Because dissociated dislocations climb and cross-slip with much greater difficulty than undissociated ones, deformation by dislocation climb is possibly of much less importance in feldspars than in quartz. It has also been observed that the feldspars contain fewer dislocation boundaries and subgrains than are commonly observed in quartz.

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