STRESS ANALYSIS OF A DEEPLY ERODED ANALOG OF THE SAN ANDREAS FAULT

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Introduction

We have been studying deformation-induced microstructures, and the temperature and stress conditions during deformation along faults which may be deeply eroded analogs of the San Andreas system. Recent studies of deformation-induced microstructures in single crystals and in polycrystalline materials indicate that the grain size, sub-grain size, and free dislocation density are, to a good approximation, dependent primarily on the differential stress and are related to temperature and strain rate only as the stress, temperature and strain rate are coupled through a flow law. Analyses of deformation-induced microstructures offer the possibility of placing major constraints on the range of stress-levels present during large-scale geologic deformation phenomena. Our recent results (Weathers et al., 1979) of a study of the microstructures in rocks from the Moine thrust in Scotland indicate that deformation along the fault occurred at a differential stress on the order of 1 to 2 kbar.

We have chosen four faults for our study of deeply eroded shear zones: the Ikertôq and Nordre Strømfjord shear zones in western Greenland, the Idaho Springs - Ralston shear zone in Colorado, and the Mullen Creek - Nash Fork shear zone in Wyoming. Collections were made across the southern margin of the Ikertôq shear zone, near the Søndre Strømfjord Air Force Base, by Dr. I. van der Molen and T.S. Olsen during July-August, 1979. Collections across the Nordre Strpmfjord shear zone will be made during the summer of 1980. Our work on the Greenland shear zones is done in cooperation with Dr. Kai Sørensen, Aarhus University, Denmark. T.S. Olsen is one of Sprensen's students who will be working with us at Cornell for the next year on this project. Olsen is supported by the National Science Foundation of Denmark. Our transportation to Søndre Strømfjord Air Force Base has been provided by the 109th Air National Guard from Schenectady, New York, and the Military Airlift Command from McGuire Air Force Base, New Jersey. Logistical support at Søndre Strømfjord was provided by the Greenland Ice Sheet Project. Collections across the Mullen Creek - Nash Fork shear zone in Wyoming and the Idaho Springs - Ralston shear zone in Colorado were made by Dr. M.S. Weathers and two field assistants during June and July, 1979. Dr. R.S. Houston, University of Wyoming, provided help in choosing sites for making measured collections across the Mullen Creek - Nash Fork shear zone.

The Ikertôq shear zone, Greenland

The Ikertôq shear zone extends from Holsteinsborg, on the coast of western Greenland, to east of Søndre Strømfjord, approximately 150 km inland. The shear zone is approximately 40 km wide and trends ENE. It cross-cuts Precambrian gneisses, which are probably equivalent to the Nuk gneisses of the Godthaab region, of approximately 2800 m.y. age. Grocott (1977) has suggested that the western Greenland shear zones are deeply eroded, Precambrian analogs of the San Andreas system. Rocks now exposed at the surface were at depths of 15 to 30 km and temperatures of 600 to 800^{o}C when they were deformed.

We have made several collections across the southeastern margin of the shear zone. The rocks in this region consist primarily of granodioritic to quartz dioritic gneisses metamorphosed to granulite facies. These gneisses are cross-cut by two sets of basic dikes. The earlier set of dikes trends E-W, approximately parallel to the shear zone; the later set of dikes trends NNE, cross-cutting the shear zone. South of the shear zone, this later set of dikes is undeformed, but shows an increasing amount of deformation going into the shear zone. Within the shear zone the dikes show extensive development of boudinage (Figure 1). The dikes are metamorphosed to amphibolite facies. We have made collections across several of the dikes; they consist primarily of amphibole and quartz.

The basement gneiss at Søndre Strømfjord is complexly folded and migmitized (Figure 2). Samples consist primarily of quartz, plagioclase, potassium feldspar, hornblende and biotite. The quartz shows extensively developed undulatory extinction, and is recrystallized along sub-grain boundaries within grains. Measurements of free dislocation densities, sub-grain sizes and recrystallized grain sizes in quartz grains from these gneisses have yielded differential stresses of 50-110 MPa, 20-40 MPa, and 20-40 MPa, respectively (Kohlstedt et al., 1979). The dislocation density within quartz grains is usually inhomogeneously distributed, and may vary from 10^8 to 3×10^9 within regions of a single grain (T.S. Olsen, pers. comm. 1979). The highest dislocation densities usually occur near the contacts with "stronger" minerals such as plagioclase.

We have interpretated the microstructure of the gneisses as indicating that a significant amount of post-deformational recovery has occurred, and that the stresses indicated by the sub-grain size and dynamically recrystallized grain size reflect recovery following deformation. The dislocation density might reflect a late, short-term, high-stress pulse. Such a stress pulse could be due to differences in the temperature and pressure dependences of the thermal and elastic properties of the several minerals which comprise the gneiss. We do not think that any of the differential stress measurements reflect the stress level during the major episode of deformation along the shear zone. Additional evidence for post-deformational recovery in the shear zone comes from the petrography of the dikes. In contrast to quartz grains in the gneiss, quartz grains in the dikes show very little undulatory extinction and no recrystallization.

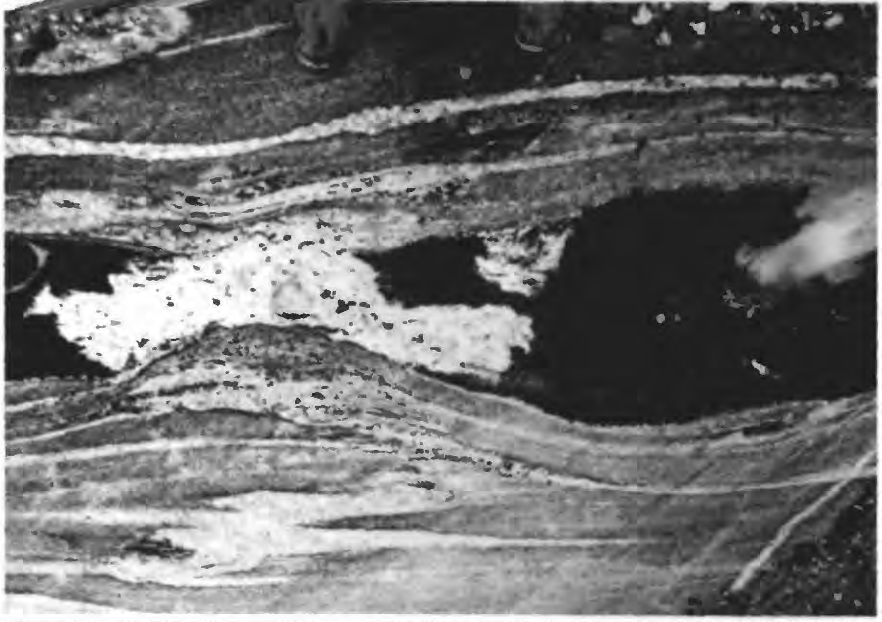

Figure 1. A boudinaged basic dike partly replaced by a pegmatite. Outcrop at the Søndre Strømfjord Air Force Base, Greenland. Field of view is about 2 meters.

Figure 2. The Precambrian gneiss at Søndre Strømfjord showing complex folding. The gneiss varies from amphibole-rich bands (black) to feldspar-rich bands (white). Field of view is about 2.5 meters.

The amphibole grains commonly form 120° triple junction. Such textures are common in rocks that have undergone significant recovery or annealing.

The Mullen Creek - Nash Fork and Idaho Springs - Ralston shear zones, western United States

We have been comparing the microstructures developed in quartzites from two shear zones in the western U.S. -- the Mullen Creek - Nash Fork shear zone in Wyoming and the Idaho Springs - Ralston shear zone in Colorado. These two shear zones are part of a belt of shear zones extending from southeastern Wyoming to northwestern Arizona which Warner (1978) has called the "Colorado Lineament" and has proposed to be a Precambrian analog of the San Andreas system.

The Mullen Creek - Nash Fork shear zone in Wyoming can be traced for over 40 km through the central Medicine Bow Mountains. It cross-cuts Precambrian basement rocks and separates older rocks (2.4 b.y.) northwest of the shear zone from younger rocks (1.75 b.y.) southeast of the shear zone (Houston, 1968). Rocks exposed along this shear zone were originally deformed at depths of 10 to 20 km and temperatures of approximately $500^{\circ}C$. We have made several collections across this shear zone from the Medicine Peak Quartzite west of the shear zone into a quartz-feldspar gneiss east of the shear zone. We have studied the development of microstructure in both the quartzite and gneiss.

At the eastern margin of the shear zone, the gneiss consists of 40-50% quartz, 40-45% potassium feldspar and plagioclase, and 5-10% muscovite. The quartz and feldspar usually occur as large (0.5 to 1.0 mm), equant grains with the feldspars partly altered and the quartz showing undulatory extinction. The quartz occasionally occurs as discontinuous bands in the gneiss. Further into the shear zone, banding in the gneiss becomes more pronounced. Quartz bands consisting of recrystallized grains with sutured grain boundaries alternate with bands consisting of granulated feldspar, muscovite, fine-grained recrystallized quartz and occasional large, relict feldspar crystals. Houston (1968) reports that banding in the gneiss becomes finer towards the center of the shear zone and that the gneiss eventually becomes a fine-grained mylonite. In the collections that we made, the gneiss is not mylonitized.

The Medicine Peak Quartzite from the western margin of the shear zone consists of large quartz grains (0.75 to 1.0 mm) with minor amounts of muscovite and kyanite. The quartz grains tend to be slightly elongated, with aspect ratios of up to 7:1. Quartz-quartz grain boundaries tend to be angular, rather than rounded. The quartz shows very little undulatory extinction and almost no recrystallization. Further into the shear zone, the average grain size of the quartzite is smaller (0.5 mm), however, there is no further elongation of the relict quartz grains.

We have measured sub-grain sizes in the quartzite and free dislocation densities in the quartzite and gneiss. The Medicine Peak Quartzite shows extensive polygonization and sub-grain development; the microstructure in this quartzite may have recovered by dislocation climb mechanisms, rather than having recrystallized by grain boundary migration, as we observed in the quartzite from the Moine thrust. Because of the lack of recrystallization, we have not been able to measure the recrystallized grain size. However, the sub-grain size in the quartzite is fairly constant across the shear zone, averaging 1.7 microns. There is a slight increase in sub-grain size towards the center of the shear zone, but it might not be statistically meaningful. The free dislocation density in quartz grains from the gneiss and in the quartzite shows a definite trend to lower values near the center of the shear zone and much higher densities near its margins. The dislocation density decreases from 13 x $10^8 cm^{-2}$ at the western margin of the shear zone to approximately 4 x $10^8 cm^{-2}$ near its center, and increases again to approximately 11 x $10^8 cm^{-2}$ at the eastern margin. These dislocation densities, assuming they were produced during steady-state deformation, would correspond to differential stresses of about 2 kbar at the margins of the shear zone and less than 1 kbar near the center. The sub-grain size suggests a relatively constant differential stress of about 1 kbar. It is possible that the sub-grain size represents the stress during the main episode of deformation along the shear zone and that the trend in dislocation density reflects a later, high-stress pulse with the dislocations becoming progressively annealed from the center of the shear zone.

The Idaho Springs - Ralston shear zone extends for approximately 40 km through the central Front Range in Colorado. It cuts through Precambrian quartz-feldspar and hornblende gneisses, biotite schists, granite and quartzite. We have made several detailed collections across the quartzite unit. This quartzite unit shows a very different style of deformation from that exhibited by the Medicine Peak Quartzite; the microstructures are typical of those developed in mylonites from classic localities such as the Moine thrust (Christie, 1963). Within the region mapped as the shear zone (Lovering and Goddard, 1950; Wells et al., 1964), we have observed small zones of completely recrystallized quartz, usually a few meters in width and spaced a few meters to several tens of meters apart. Approximately midway between two completely recrystallized zones, relict quartz grains have aspect ratios of up to 10:1, samples are approximately 25 to 35% recrystallized to 15-micron grains. Recrystallization occurs primarily along quartz-quartz grain boundaries. Samples taken closer to the completely recrystallized zones show more extensive elongation of relict grains, with aspect ratios greater than 100:1, and with a greater percentage of recrystallization.

The variation in aspect ratios of relict quartz grains, approaching the recrystallized bands, suggests a variation in strain. However, the differential stress during deformation appears to have been constant across the entire width of the shear zone. The dynamically recrystallized-grain size within both completely recrystallized and partly recrystallized samples averages about 15 microns. Sub-grain size in samples taken across the entire width of the shear zone varies only from about 0.5 to 4.0 microns, and averages about 2 microns. Similarly, the free dislocation density does not vary significantly within the shear zone, ranging from 3.5 to $6.0 \times 10^{8} cm^{-2}$. Because the recrystallized grain size, sub-grain size, and free dislocation density all indicate a stress of about a kilobar, we suggest that along this shear zone there was a long-term deformation event at a differential stress of approximately 1 kbar during which time the observed microstructure was generated. This agreement among the three paleopiezometers for this shear zone is in contrast to the Moine thrust where the recrystallized grain size and dislocation density indicated different differential stresses (Weathers et al., 1979).

We are still studying the difference in style of deformation between quartzites from these two shear zones. The extensive recrystallization and elongation of relict grains in the quartzite from the Idaho Springs - Ralston shear led us to suspect that perhaps this quartzite contained more water than the quartzite from the Mullen Creek - Nash Fork shear zone. We have begun infrared spectroscopy studies on samples from both shear zones to measure the water-content, but so far our results have been inconclusive. However, we intend to continue this study to try to resolve the problem of the different styles of deformation along these two faults.

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