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PENROSE CONFERENCE REPORT: FINE-GRAINED FAULT ROCKS

Jerry Magloughlin (University of Illinois, Department of Geology, 1301 West Green Street, 245 Natural History Building, Urbana, IL 61801)
Frederick Chester (St. Louis University, Department of Earth and Atmospheric Sciences, 3507 Laclede Avenue, St. Louis, MO 63103)
John Spray (Department of Geology, University of New Brunswick, Fredericton, N.B., E3B 5A3, Canada)

INTRODUCTION

Tectonic processes on earth tend to be partitioned into zones of concentrated deformation. It is here that fault and shear systems of various dimensions can develop. The products of such focused deformation are typically fine grained. Consequently, these rocks can be difficult to study, at least in the field if not under the microscope, and they may present problems of identification, definition and interpretation. For example, it may not be possible to distinguish an ultramylonite from an ultracataclasite at the macroscopic scale of observation, yet these two rock types are generated under markedly different values of strain-rate, pressure, temperature, fluid composition, and fluid pressure. Aside from problems of nomenclature, we need to improve our knowledge of fine-grained fault rocks in order to reveal the underlying controlling mechanisms operating in fault and shear zone systems. This is particularly the case for the seismogenic regime where there are clear socioeconomic and environmental implications for man.

Because of these and other outstanding problems, a Penrose conference was held August 31 - September 4, 1995 in Leavenworth, Washington, in the North Cascade Mountains of Washington State. The 78 participants included 30 international participants from 12 countries as well as 12 graduate students. The conference was partially supported by the Geological Society of America, the National Science Foundation, and the U.S. Geological Survey Earthquake Hazards Reduction Program.

The objectives of the meeting were 1) to review existing field and laboratory data and discuss the implications and applications of these data to further our understanding of fault rock genesis; 2) discuss the importance of multi-disciplinary studies, particularly with respect to fluid-rock interaction during faulting, and outline future research priorities using a multi- disciplinary approach to investigate fault rock genesis and fault zone properties, and 3) facilitate the application of research results to societal needs. An important goal was to bring together experts on all aspects of fault rock study. Research expertise included experimental rock mechanics, field studies, fluids in fault zones, deformation mechanisms involved in fault rock formation, physical properties of fault rocks, petrology, and stable and radiogenic isotope analysis of fault rocks and shear zones.

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Specific questions posed prior to the meeting were 1) What do specific fault rocks reveal about the mechanical properties, and therefore the associated geological hazards, associated with a fault or shear zone? 2) What can be inferred about the timing, volume, and composition of fluids flowing though faults and shear zones with reference to specific coeval fault rocks at various crustal levels? 3) What do the textures, particle size distributions, and operative deformation mechanisms observed in naturally and experimentally formed fault rocks, reveal about such parameters as temperature, stress, and strain rate? 4) Which fault rocks are amenable to geochronometric techniques? 5) What are the spatial, temporal, and genetic relationships among the fine-grained fault rocks? 6) How can a multi- disciplinary approach to fault rock studies better elucidate the evolution of faults and shear zones? 7) Does the current classification scheme require modification, extension, or loosening? 8) Should fault rock terminology be developed or modified for better application in the field? 9) How do fine- grained fault rocks influence fluid flow in fault and shear zones?

The first day of the conference was spent in the field, led by Jerry Magloughlin, where the group observed a variety of fault rocks in a transect through part of the Nason Terrane in the North Cascade Mountains. The fault rocks included plastically deformed migmatite, gneiss and mylonite, through rocks of a more brittle nature, pseudotachylyte and cataclasite, to faults and fault gouge representative of deformation at shallower crustal levels. We observed brittle and ductile features in the tonalitic rocks of the Cretaceous Mount Stuart Batholith located southwest of a suspected major suture, the Rock Lake Shear Zone. We visited mylonitic peridotites of the White River ultrabasic body were visited, as well as pseudotachylytes and cataclasites developed in interlayered schists and gneisses of the Wenatchee Ridge Gneiss along the Little Wenatchee River. The trip provided an excellent forum for viewing fault-related rocks from the brittle through to the ductile fields as well as for the participants to become acquainted with each other.

The following three days of the conference were devoted to oral and poster presentations covering field, experimental, theoretical, and analytical aspects of fine-grained fault rocks. Presentations and discussions were divided into five theme sessions: 1) deformation and recovery mechanisms, 2) rheology of fine grained fault rocks, 3) the role of fluids in faulting and fault rock genesis, 4) the relation of fine-grained fault rocks to the seismic cycle, and 5) advanced methods for study of fine-grained fault rocks. Each session was initiated by a keynote speaker, and an additional 12 speakers made presentations within the five categories. The sixth and final session involved a summary and discussion of each of the preceding 5 sessions. The summaries and discussions were led by five of the conference participants. More than 40 posters were displayed during the conference. Considerable time was dedicated to formal and informal discussion periods, and to the poster displays, so that all participants had the opportunity to share their ideas. Many participants commented that the group round table, discussion was one of the highlights of the meeting.

We feel the conference was a considerable success. Washington provided perfect weather for the field trip right on through the final evening when some of the participants did their best to extend discussion into the early morning hours until just before the vans departed. Most participants left the conference with the feeling that significant progress had been made in our understanding of fault rocks and that the future will provide the opportunity for very fruitful research.

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MECHANISMS OF DEFORMATION AND RECOVERY

The opening session was dedicated to the mechanisms of deformation and recovery. Jan Tullis reviewed grain scale deformation mechanisms, including fracture/frictional sliding, cataclastic flow, pressure solution, dislocation creep, diffusion creep, and grain boundary sliding, and focused on feldspathic rocks. While there is a fairly good understanding of the flow laws for quartz, feldspars are more uncertain, and in polymineralic aggregates, in the dislocation creep field for example, behavior is difficult to predict. The role of water is another variable of major importance in all the deformation mechanism regimes.

Martin Burkhard described the spectacular Glarus thrust and its thin ultramylonite zone previously interpreted as representing superplastic flow. He pointed out several contradictions to the superplastic model, and described possibly enormous volumes of fluids apparently collected below the thrust and expelled toward the foreland.

Sue Agar described shear zones in the oceanic crust near the Mid-Atlantic Ridge that displayed an interesting interplay of syn-magmatic and high-temperature deformation. She reported evidence for melt-assisted grain boundary sliding, dislocation creep, brittle fracturing, and cataclastic flow along dike margins.

It is well known that fine grained fault rocks form due to a variety of grain-scale deformation mechanisms. Microstructures also reflect the operation of recovery processes, such as crack healing and dynamic recrystallization. In some cases, particularly for steady-state deformation, the recovery processes are as important as the deformation mechanism in dictating microstructure and flow behavior. Both deformation and recovery processes are thermally activated and will be important over a restricted range of crustal conditions. Much of what we know about these mechanisms comes from laboratory experiments. Because of technological restrictions, experimentalists do not try to simulate crustal conditions, but rather impose conditions to activate the various deformation and recovery processes. The well-known technique of trading temperature for time is a method to activate processes in the laboratory time frame that occur over geologic times in the earth. The experimental work to date has largely been focused on defining the flow laws and characteristic microstructures for each type of deformation and recovery process. Scaling and extrapolation of laboratory relations to nature are the two main difficulties because experiments generally are done on small samples at high deformation rates.

Classifications of fine grained fault rocks reflects the relation of deformation and recovery mechanisms to microstructures. Most participants are fairly satisfied with the fault rock terminology presented by Sibson [1977] that distinguishes fault gouge, ultracataclasites, ultramylonites and pseudotachylytes. It is generally agreed that the mylonite series involves mostly crystal-plastic deformation processes, and that gouge and cataclasites involve mostly fracture and cataclasis. However, in most fault rocks there is textural evidence for variations in the combination and competition of processes in space and time. This is probably particularly true of seismogenic faults that experience cycling of deformation rates over many orders of magnitude. Nonetheless, there is a general sequence of gouge to cataclasites to mylonites from the increasing pressure and temperature with depth in the crust. The association of deformation and recovery mechanisms with

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metamorphic grade is sufficiently robust that some participants suggested that fabrics could be used as crude geothermometers, particularly for polyphase rocks.

Many participants presented field based observations of brittlely deformed fault rocks. These rocks are some of the more difficult to study due to the poor cohesion, discontinuous deformation, and presence of many phases often including clays. There was some discussion of the difference between gouge and ultracataclasite. The association of these fault rocks with metamorphic grade implies a genetic distinction. It appears the distinction is the lack of cohesion in the gouges, and that the terms are used in the field to distinguish incohesive from indurated cataclastic fault rocks. However, it is clear that some ultracataclasites could simply be cemented gouge. Critical to understanding faulting mechanisms is the timing of the development of cohesion. It is possible for cohesion to develop with time between grains in intimate contact. In most cases of the crust, cohesion probably develops by healing and sealing of microfractures. Cohesion could develop continuously during cataclastic flow, or between episodes of brittle deformation, or completely after the end of tectonism. The timing of cohesion development is probably important to mechanical behavior, and may be intimately related to the strength recovery of brittle faults that must take place during interseismic periods.

A number of participants presented observations of flow fabrics in gouge and cataclasite. In some cases the structures are quite remarkable, particularly the flow patterns about irregular contacts between wall rock and gouge, and gouge ponding, extrusion, and folding. These observations prompted some discussion of the extent that gouge and ultracataclasite is fluidized during faulting. Although it is typically assumed that flow structures are associated with steady creeping behavior, the possibility of fluidization during seismic slip events also could conceivably produce flow structures. It is generally agreed that we have much to learn regarding mechanism of deformation within the ultra-fine-grained cataclastic rocks.

Laboratory study of deformation across the brittle to plastic (cataclasite to mylonite) transition has been investigated extensively. Although there is still much interesting and useful work to do, it appears we now have a fairly good understanding of the main grain scale deformation and recovery mechanisms in monomineralic aggregates of halite, calcite, quartz, feldspar and olivine. Although each of the minerals undergo a brittle plastic transition, there are important differences in their behavior. For example, minerals with good cleavage like halite, calcite and feldspar are apparently likely to exhibit cataclastic flow and grain-size sensitive flow, whereas quartz does not tend to do so. For all these minerals, different creep mechanisms have been identified and they are defined by the dominant recovery process. Two important recovery processes for quartz and feldspar are grain-boundary migration recrystallization and rotation recrystallization. Although these processes are fairly well understood in the laboratory, there is still uncertainty in application to the field. For example, field studies of mylonitic rocks would suggest that dislocation creep and recrystallization might occur at somewhat lower temperatures than predicted by experiments. In addition, the limited experimental work on polymineralic rocks demonstrate that it is not trivial to predict behavior based on the results of monomineralic aggregates alone.

Experiments have demonstrated the importance of deformation path on localization of strain, as well as on the deformation mechanisms and resultant fabrics. For minerals that can deform by grain size sensitive mechanisms, brittle faulting and attendant grain size reduction can serve to localized ductile shear zones. The switch in mechanisms from dislocation creep to grain size sensitive mechanisms by dynamic recrystallization, though often suggested, has yet to be clearly demonstrated for any mineral. Based on experimental work to date, a switch in mechanisms from dislocation creep to grain size sensitive mechanisms by dynamic recrystallization seems likely for calcite but unlikely for quartz at geologic rates. A number of other softening processes were demonstrated based on field study, including reaction transformation softening in continental shear zones and partial melting and melt migration processes at mid-ocean ridges. Studies of large displacement transform and detachment faults illustrated the difficulty in identifying deformation path as well as the important grain-scale processes in the localized zones of shear. It is clear that some important processes may leave little in the way of fabric modification or very subtle features, which makes it difficult to demonstrate their importance. An example discussed at the conference was the role of brittle processes in mylonites, which may be extremely important to localized fluid flow and to rheology, but will tend to produce only ephemeral features.

There was considerable discussion pertaining to a perceived division between the the experimentalists and those working on natural rock systems. Experimentalists pointed out a lack of information on many strain rates and lithologies, and encouraged the latter group to speculate on deformation mechanisms in their studies of natural deformation. Those working on natural rocks encouraged the experimentalists to more thoroughly explain how to apply experimental data to natural settings.

Shear zones were a major topic for discussion. Some fundamental points addressed included the recognition that we can no long assume that simple shear alone is responsible for producing the deformation, but rather that there is likely some component of pure shear. Also, shear zones are internally variable, and differences as subtle as grain size variations can produce a change in the deformation mechanism(s), so that different mechanisms can be dominant simultaneously in adjacent layers. While this complicates interpretation of shear zones, it can also be an aid, because spatial and temporal heterogeneity of a shear zone may allow the recording of different stages in its evolution. The operation of one deformation mechanism can even produce a change to a different mechanism. For example, a cataclastically deformed zone can lead to dilation allowing fluid infiltration, which in turn allows the operation of a plastic deformation mechanism. There was a call for more complex initial models of shear zones, because simple models are appended onto until they become unrealistic and then need to be discarded. Much discussion also revolved around strain partitioning, and the challenges this introduces. Why in some cases does strain remain localized in a single, narrow zone, while in other cases it is partitioned into the margins of the zone?

Another point that was mentioned at various junctures is that many of us are ready to admit there has been a tendency (but pervasive in many fields?) to illustrate, photograph, and interpret structures on the basis of what are relatively rare but considered to be ideal, features. This has surfaced for two reasons with respect to shear zones: first, with the recognition that many classic, (and commonly photogenic) microstructures are rare, and second, with the admission that ideally simple-shear shear zones may be rare. There does seem to be a tendency toward more investigation of less photogenic (or more thoroughly uglified, rocks, to use Rick Sibson,s term) but probably more common and important rocks and structures.

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A major point was that in contrast the Penrose Conference on Mylonites, this Penrose did not focus on terminology. Instead, it focused on processes, with many detailed descriptions of observations of both experimentally and naturally deformed rocks.

RHEOLOGY OF FINE-GRAINED FAULT ROCKS

The second session was devoted to the rheology of fine- grained fault rocks. In the opening talk, Ernie Rutter posed two fundamental questions: how is the process of grain-size reduction accomplished, and what are the mechanical properties of grain-size reduced rocks? He pointed out that preferred orientation cannot be used to distinguish grain-boundary flow from dislocation creep, and that the rheological information currently available for rocks at high strain is limited owing in part to experimental limitations.

Toshi Shimamoto reported on brittle to fully plastic deformation of halite, and pointed out the dearth of studies on fine grained fault rocks.

Robert Holdsworth reported on reactivation of the Outer Isles Thrust system (Scotland), where late movement occurred producing strike-slip phyllonite zones. He speculated that phyllonite zones in general might be indicative of reactivated basement faults and therefore their physical properties are important to fault zone rheology. The role of phyllosilicates in deformation, ubiquitous though they are, was overall concluded to be poorly understood. There was a call for new experimental work in this area, perhaps initially as impurities, in quartz or feldspar dominated aggregates.

Cees Passchier described what may be the more common type of shear zone where deformation does not occur by simple shear alone. He described the concept of the material line attractor, toward which material lines rotate in the case of general non-coaxial shear zones, and how the assumption of simple shear and stretching lineations parallel to flow direction can lead to erroneous estimates of strain and displacement direction.

Experimental work has not only helped to define deformation and recovery processes, but quantify mechanical behavior as well. We generally use a simple Coulomb failure criteria to describe fault behavior in the brittle, frictional regime. However, there is apparently growing concern that this simple description of brittle failure may not be applicable in some mature faults, and certainly is insufficient to explain brittle fault rock genesis and some aspects of faulting phenomena. The mechanical behavior of brittle fault rocks containing phyllosilicates and in situations where significant pressure solution processes are operating are particularly important to define. Observations of deformation across the brittle to plastic transition indicate that behavior in the transitional regime is pressure dependent (frictional) even though the microstructures may record significant crystal plasticity. Descriptions of rheology in the transition flow regime is generally lacking. There is fairly good consensus on the creep rheology of quartz and calcite, but other crustal minerals are less well understood. Characterization of the creep behavior of feldspars and phyllosilicates will be an important step to quantify fault rock rheology. In addition, it will be important to investigate the behavior of polymineralic aggregates in experiments as well as by theoretical modeling.

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Rheology at very high strains, as occurs in many shear zones, is also an area of active research. Several participants described new testing machines or novel approaches to looking at high strain behavior. In conventional experiments that can achieve only limited strains, often steady strength behavior is achieved even though the microstructure continues to evolve. Many questions exist regarding the behavior in very high strain zones as occurs in nature. Some interesting preliminary findings are that the common assumption that flow by grain boundary sliding produces random crystallographic fabrics is not correct. In these discussions some attention was given to superplastic behavior. It is important to realize that superplasticity is not mechanism specific, but rather is phenomenological and defined by a creep law with a stress exponent of less than 2. There is still work necessary to define the mechanisms that lead to superplasticity in fine grained fault rocks.

THE ROLE AND NATURE OF FLUIDS

The third session involved talks on the role and nature of fluids in fault rocks, faults, shear zones, and faulting. Stephen Cox posed the problem of determining the fluid flow regime for natural faults. Major volumes of fluids have been demonstrated for particular faults. At high pressure, the rate of crack growth increases resulting in a porosity increase but not permeability. The episodicity of a fault is an important element in fault mechanics, with some fault zones recording 1000-2000 individual episodes. Cox interpreted a suite of cataclasites to be purely seismically generated.

Brad Hacker discussed the possible role of low-grade metamorphic devolatilization reactions on seismicity during the burial of sedimentary rocks.

Ann-Marie Boullier discussed a detailed fluid inclusion microthermometric and Raman spectroscopic study of extensional and fault veins from Quebec. She was able to discern four compositions of fluids, sometimes linked to specific orientations of healed microcracks, and interpreted the results as supportive of Rick Sibson,s fault-valve model.

Andy McCaig discussed the permeability of faults and shear zones, and posed the questions of the degree and longevity of permeability enhancement. He also suggested some mineralogic and petrologic indicators of pervasive versus channelized fluid flow, such as the nature of zoning in feldspar over a small area.

Circulation of fluids is important in a number of geodynamic settings, such as in subduction zones and in plutonic regions. It is well known that fault zones may serve as conduits or barriers to fluid flow. Depending on the geometry of the fluid flow field and the geometry and permeability structure of faults, faults may serve to focus fluid flow and to establish local sources and sinks for fluids. There is much evidence for the involvement of fluids in faults, and the physical and chemical effects of fluids on fault rocks may be profound, particularly for the fine grained component of fault zones. Thus, it was anticipated that there would be much interest at the conference in the role of fluids in the genesis of fine-grained fault rocks.

There is increasing information from experiments on the relation of porosity and permeability in rock undergoing microscopic brittle deformation. However, at this time we have little basis for predicting permeability of fine grained fault rocks during deformation. Important questions include the magnitude of permeability modification during deformation and the mechanisms by which permeability is changed. Because we know that permeability is often enhanced in active fault zones, and faulting represents localization of strain, it may appropriate to classify the type of fluid flow in terms of strain localization and periodicity of deformation. End member types of flow in such a classification would include pervasive-continuous flow and channelized-transient flow. Although wide belts of mylonite typically represent distributed and continuous deformation suggesting pervasive-continuous flow, examples of microscopic features in mylonitic rocks indicative of channelized-transient flow were discussed. In such rocks, microscopic criteria for flow characteristics include preserved pathways (veins), sources and sinks of mobile elements, consistency of reaction progress and zoning patterns in porphyroblasts, and the continuity of such features within large regions of the rock. In more brittle fault zones, channelized and transient flow is indicated by vein networks, crack-seal structures, and banded cataclasites. Although many of these features do not record the amount of fluid in the system, the sheer size of vein networks in some faults, such as in many gold-hosted quartz deposits, indicate substantial volumes of fluid.

Faulting in the crust may produce local heating and cooling events leading to metamorphic reactions and the generation or removal of pore fluids. However, reactions will not be sustainable unless there is sustained burial of the crust. Thus in many cases the volume of fluids involved in faulting may not be large. In these systems the relations between deformation, pore fluid pressure, and the activity of water may be complex. Even for the most simple cases of devolatilization reactions in closed systems, it is necessary to consider processes such as the volume changes associated with reactions, and whether changes in the volumes of porosity, solids and liquids will result in pore fluid pressure increase or decrease. In considering chemical fluid rock interactions, the effects of mean stress and pore fluid pressure on the activity of water must be considered. It was suggested that in some prograde and retrograde environments, the rate of deformation may be largely controlled by the rate at which fluid is added or removed from the system rather than being controlled by thermally activated deformation processes.

Some concepts upon which there was extensive agreement included the notion that the upper crust is wet, and undergoes episodic deformation, leading to fluctuating or cyclic processes, including changes in fluid pressure, porosity, and permeability. Also, it has become very clear that the fluid history is a vital factor for consideration in any complete study of a fault zone, owing to its effect on diffusive mass transfer, dissolution and precipitation, changes in the bulk chemistry of the rock, and its role in fracture propagation.

In the review session for this topic, some major questions included the nature of the fracture-controlled plumbing system, pathway evolution and the degree of pathway closure with time, the volumes of fluid, the continuous or transient flow of fluids, the directions of flow, and the fluid sources and sinks. More information is needed on the permeability and porosity of gouge, which may require in situ measurements. Another complication is that fluids passing through fine-grained fault rocks may leave no record of their passage, at least as can be detected through the common methods.

SEISMIC CYCLE

The fourth session focused on the relation between fine- grained fault rocks and seismicity, or the seismic cycle. Rick Sibson initiated this session by discussing the nature of fault behavior with special reference to the role that fine-grained fault rocks play in the recognition of single slip events in major displacement fault zones, and to the development and modification of the fault rocks during the strain accumulation, anelastic prefailure deformation, main slip, and aftershock phases. He noted that so-called aseismic, faults can actually host large numbers of microearthquakes. A typical stress drop during a major slip event is about 100 bars. The interseismic period can vary by orders of magnitude, from 101 to 106 years. Most slip events producing melt are likely to have formed under dry conditions because a small increase in temperature can increase Pfluid and cause slip weakening. An important question is the dampening of seismic cycling with increasing depth.

Steve Wojtal described the general nature of the fault rocks present along thrust faults in the foreland setting. These boundaries are typically envisioned to be planar contacts, but actually are fault zones often more than a meter thick. The cataclasites are derived from carbonates, shales, quartz-rich sediments. The fault zone may be composed of different fault rock types sharply bounded by discontinuities, or may be gradational contacts. The cataclasites are commonly very fine- grained, and display evidence for fracturing as well as plastic flow.

Uwe Reimold reviewed Shand,s original pseudotachylytes from Vredefort, South Africa. The pseudotachylytes here are impact-related rather than related to tectonic events. Several generations of pseudotachylytes are recognized, with the early generations possibly related to shock wave propagation while later veins may be related to large-scale gravity slumping.

The relation of fine grained fault rocks to the seismic cycle was a topic that elicited much interest and discussion amongst participants. In fact one well-known and outspoken participant suggested the only reason to study fine grained fault rocks is because they may reveal something about the earthquake rupture process. An important question that was repeatedly mentioned is how do we distinguish mode of slip in ancient fault zones based on fault rock structure. Or more specifically, is the presence of pseudotachylyte in faults the only indicator of seismic slip that we can use confidently? It is important to clarify the definitions of seismic and aseismic slip as these terms originated in the field of seismology. It appears that most crustal faults are seismic. The San Andreas fault in California is an important case as it contains both seismic and aseismic segments. However, it should be noted that the aseismic, creeping sections of the fault are actually characterized by continuous generation of microseismic events. Thus, mesoscopic and microscopic scale samples may contain structures produced during microseismic events within faults that would be regarded by seismologists as aseismic. Seismologists also classify earthquakes on the basis of rates of slip and slip duration. Normal earthquakes have slip duration on the order of seconds, whereas longer duration and lower slip rates produce events referred to as slow earthquakes, quiet earthquakes, and over the longest duration, creep events. Thus the real question regarding structural criteria in fault rocks for seismic and aseismic slip actually should be posed in terms of the rates of deformation that produce fault rock structures.

As a group we have been very careful about interpreting brittle fault rocks as the products of seismic slip events. There are several structures in brittle faults from shallow crustal environments that indicate episodic deformation, such as cataclasite porphyroclasts in cataclasites, banded cataclasites, and crack-seal type structures. To be completely rigorous, we must state these features are products of episodic deformation. However, many participants feel that we can assume cataclastic rocks are the products of seismic slip events unless demonstrated otherwise because so many crustal faults appear to be seismic. In this view it is the cataclasite produced by low rates of deformation that is the rare structure. Another view that somewhat challenges dogma is the interpretation of mylonites as indicating only steady, aseismic creep. Careful analysis of earthquakes along crustal faults, such as the Loma Prieta earthquake on the San Andreas system which nucleated at a depth of 18 km, suggests the base of the seismogenic regime is at temperatures of approximately 450 C, somewhat greater than typically assumed. At such conditions quartz should deform via crystal plastic mechanisms and classic mylonites should be produced.

The issue of seismic versus aseismic criteria within fault zones was a frequent topic of discussion. Pseudotachylyte was frequently mentioned as the only reliable indicator of seismic slip, but even this is complicated in unusual settings. Pseudotachylytes have been described from impact settings, landslides, as well as the typical tectonic, setting. In impact settings, such as Vredefort and Sudbury, shock melting and frictional melting may both contribute melts to form pseudotachylytes,. However, in the tectonic setting, there was a call against the use of pseudotachylyte as a junk, term for unidentified black vein-like rocks. It is also possible that pseudotachylyte zones may not be associated with typical seismic faulting, but perhaps only initial slip within crystalline rocks, possibly because of easy availability of water, which could suppress frictional melting. The problem of seismic versus aseismic field indicators may be further resolved into the question of indicators of various slip rates. There may well be many poorly-understood structures that may be indicative of particular slip rates, or at least seismic rates versus aseismic rates.

TECHNIQUES

The fifth session dealt with advanced methods for study of fine-grained fault rocks. In the opening talk for this session, Carol Simpson described initial localization mechanisms, reaction softening, mechanical softening, and strain magnitudes, emphasizing the importance of the progressive deformation history. Fluids play a vital role in the operative deformation mechanisms by inducing microcracking, initiating diffusional mass transfer, and promoting the growth of new crystals in favorable orientations for slip. Newly grown phases are typically small and strain-free and thus relatively weak.

Joe White described high strain zones from several locations emphasizing the need and utility of TEM studies to understand the deformation mechanisms and other details of the deformation.

Peter Vrolijk discussed the modification of the mineralogy and material properties of clay-rich fault zones undergoing brittle deformation. Smectite dissolution and illite growth are enhanced in such zones, as is the loss of radiogenic argon with important implications for geochronology.

Bob Maddock described multiple dating techniques applied to gouge from the Äspö Hard Rock Laboratory in Sweden. Paleomagnetic dating, K-Ar dates on illite, and ESR dating do not agree because they fundamentally date different events. The finest fractions of probably authigenic illite yielded dates apparently post-dating the last movement on the fault.

Because the meeting was focused on the fine grained fault rocks, a number of advanced techniques for analysis at the microscopic scale were discussed. It is important to study at the grain and crystal lattice scales because the fundamental processes of deformation do not necessarily reveal themselves at the mesoscopic level. The value of imaging with electron microscopy has certainly been demonstrated, and is an important technique when using modern microchemical and dating techniques. In many cases the most difficult aspect of such studies is sample preparation and characterization. There always will be the problem of relating what is seen at the microscopic scale to the larger tectonic picture, but the rewards of careful microstructure analysis can be great. This was best demonstrated at the meeting by studies of clay-bearing fault gouges. Remarkably, even the finest grained clay components of fault rocks can preserve isotopic signatures and microstructures of deformation events over geologic times. Observational and experimental studies of clays and other phyllosilicates would seem to be a area of potentially very fruitful research.

Fine grained fault rocks commonly are localized within a broader zone of shear. It is probably fair to say that natural genesis of fine grained fault rocks rarely reflects the common idealization of steady flow within zones of simple shear. The heterogeneous deformation characteristic of fault zones does make analysis difficult, particularly if exposures are incomplete. A technique of structural geology that has proven useful to understanding fault rock genesis is the study of small, somewhat simpler structures. An example at the meeting was provided by the study of tip regions of brittle faults to address models of fault growth. However, some of the many processes that can lead to localization and development of fine grained fault rocks may only be amenable to study in mature, large deformation structures. In addition, some problems such as the apparent weakness of transform faults like the San Andreas or the dynamics of earthquake rupture may also require looking at large structures. A key concept in this case may be that the heterogeneity of fault zones should be studied because it may provide a record, albeit possibly incomplete, of deformation path.

Analysis of combined simple and pure shear in even the most simple idealized shear zones leads to the conclusion that a great variety of structures are possible for only small variations in applied strains or paths. It is clear that seemingly contradictory kinematic indicators may be produced in the same shear zone and that mineral elongation lineations may or may not form parallel to the direction of shear. However, it may be possible in some cases to use small structures such as shear bands and porphyroclasts tails to infer something about strain conditions and deformation path.

A continuing major difficulty in the study of fine-grained fault rocks is the lack of firm pressure and temperature constraints. In high grade rocks, e.g. ultramylonites, fine grain size can be a problem, but at low grades, e.g. in the case of gouge and cataclasites, there are commonly no applicable thermobarometers, and disequilibrium is likely a problem for traditional exchange thermometers.

Laser techniques were hailed as a major improvement over previous methodology for radiogenic, stable isotope, and bulk chemical analysis for fine-grained fault rocks. The advantages of in situ analysis, small sample size, low blank, rapidity of analysis, and ability to vaporize chemically refractory phases offers great promise in the study of fine-grained fault rocks.

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PENROSE PARTICIPANTS

Susan Agar
Joseph Allen
Mark Anders
Hans Ave Lallemant
Nellena Beedle
Mike Blanpied
Gerard Bossiere
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Michael Bunds
Martin Burkhard
Luigi Burlini
Chris Butler
Jonathan Caine
Sue Cashman
Fred Chester
Trenton Cladouhos
Simon Christopher Cox
Stephen Cox
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Martin Olsen
Cees Passchier
Lynn Pryer
Ze'ev Reches
Uwe Reimold
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John Spray
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Joe White
Chris Wilson
Steve Wojtal
Xin-Yue Yang

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