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Penrose Conference Report

Applications of Strain: From Microstructures to Orogenic Belts

Conveners
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A Penrose Conference on "Applications of Strain: From Microstructures to Orogenic Belts" was held on September 9-13, 1992, near Halifax, Nova Scotia. There were 71 participants, including 5 from Canada and 15 from Europe and Japan. They represented a broad range of backgrounds, from academic to industry, and spanning such disciplines as structural geology, geodynamical modeling, seismology, and petrology. The conference also benefited from the assistance and active involvement of its 15 student participants.

The conference program included 3 days of meetings and 2 days of field trips. Field trips were lead by Jack Henderson, Mariette Henderson, and Tom Wright and focused on the deformational history of the Lower Paleozoic Meguma Group, which is beautifully exposed along the Atlantic coast of Nova Scotia. The Meguma contains a variety of mesoscale structures, but even more important are the presence of useful strain markers, such as worm burrows, sand volcanoes, dewatering tubes, quartz veins, fiber overgrowths, and bedding/cleavage geometry. The field trip leaders defended their interpretation that deformation of the Meguma Group and the formation of a well-developed pressure-solution cleavage was associated with large volume strains. They argued that the volume strain reflected both a loss of porosity and also a loss of mass. This interpretation, that low temperature deformation might be attended by wholesale loss of mass at a regional scale, remained a contentious and controversial issue throughout the conference.

An important objective of the conference was to ensure that a significant amount of time was devoted towards informal presentations and discussions. As such, we limited the

number of oral presentations to 3 to 4 per session. The rest of the time was devoted to a discussion period and poster presentations. Each discussion period also included unscheduled "comment" presentations, where an idea was briefly described using no more than 2 to 3 slides and 5 minutes. About 20 people made comment presentations. This format provide an important degree of flexibility that helped to ensure that discussions were not too highly structured or influenced by the oral presentations. About 2 hours of each session were devoted to poster sessions, which provided another format for informal discussion and exchange.

We want to stress that the much of the success of the conference stemmed from the informal exchanges outside of the oral presentations. Unfortunately, it is difficult to provide a useful account of those activities. Thus, in this report we have chosen to highlight the oral presentations because they help to illustrate the topics that were covered.

The first session was entitled "New Methods, Computer-Aided Analysis, and Primary Fabrics". Declan De Paor provided a computer-illustrated demonstration of the various tools that he employs in strain analysis, with an important emphasis on a graphical approach. Two particularly interesting topics were the analysis of steady and accelerating flow under conditions of general shear and the use of Beizier curves to illustrate graphically the implications of strain compatibility. Norman Fry provided a cautionary review of the density methods for strain analysis, and discussed possible extensions of his Fry method. John Stamatakos discussed the current status of magnetic anisotropy measurements as an indirect but quick method for measuring strain in bulk samples.

The second session was "Strain, Vorticity, and Microfabric Development". Win Means presented a lucid discussion of continuum mechanics concepts as applied to microfabric analysis, which helped to establish a common conceptual basis for subsequent discussions about the importance and relevance of κ_N, the kinematic vorticity number. κ_N represents an instantaneous measurement of the degree of noncoaxiality of the deformation at a point (in a more casual fashion, it can be viewed as a relative measure of the simple shear component of the deformation). Means emphasized the importance of selecting an appropriate reference frame. Microfabrics are best analyzed using an internal reference frame that considers the deformation of the material at a point relative to the instantaneous local

stretching axes. This acknowledges the fact that the microfabric evolves as a result of local stretching, and without a direct reference to an external or geographic reference frame. Simon Wallis discussed how rotated porphyroblasts can be used to reconstruct the pattern and character of general shear in an orogenic wedge, with the objective to determine how tectonic processes might contribute to unroofing of the metamorphic interior of the wedge. Norm Gray introduced a new method for analyzing inclusion trails in rolled garnets. The method uses the Jeffery equations, which describe the rotation of a rigid inclusion embedded in viscously flowing matrix, to invert for the strain and vorticity history of the matrix around the garnet.

The third session was "Volume Strain, Fluid Flow, and Mass Transfer". Ron Vernon provided a comprehensive review of this topic, which helped to put the various types of evidence, such as geometric strain measurements, textural observations, and chemical measurements of differentiation and mass loss, into an appropriate perspective. Charles Onasch presented a detailed analysis of volume strain in quartz arenites from the Appalachians. He showed interesting evidence that microveins within individual detrital grains could account for a local intragranular volume increase of 5 to 17%, whereas interpenetration at grain boundaries indicated from 0 to 30% volume loss. Jay Ague provided a general review of the chemical approach to measuring volume strain. Given an appropriate immobile or conserved element, the chemical method can be used to measure relative changes in mass. However, the method is insensitive to volume strains caused by changes in porosity or average grain density, which makes it difficult to compare the results of the chemical method with those determined from geometric methods. Ague also stressed that an essential requirement for the chemical method is that the protolith have a well defined composition with relatively little variation across the study area.

The fourth session, "Macroscale Structures", focused on how observations at a local scale might be integrated to the scale of the outcrop and larger. Cees Passchier gave a intriguing talk on how structures developed under conditions of general ductile shear. Passchier's presentation highlighted the importance of κ_N as a general descriptor for steady two-dimensional deformation, but it also showed the difficulty of using this descriptor in geologic studies where the deformation might have been unsteady and/or three dimensional.

Terry Engelder presented the results of an integrated strain study of Appalachian siltstones, for which it is possible to compare various strain and stress methods, including magnetic susceptibility, chlorite fabric, Fry center-to-center, and deformed fossils. David Anastasio reviewed a study of folding mechanisms in the Lost River Range, Idaho, using fiber overgrowths on pyrites as a record of incremental strains. Christian Teyssier reviewed the use of strain measurements for the study of emplacement mechanisms for granites. He emphasized the role of particle interactions and concluded that this mechanism should reduce the degree of preferred shape orientation.

The fifth session was "Orogen-Scale Structures". John Ramsay discussed the difficulties of relating outcrop-scale strain measurements to the orogen-scale displacement field. He argued that strain data must be interpreted in the context of strain compatibility and that this type of analysis usually revealed the need for volume strain, at least at a local scale. Arnaud Pecher reviewed the structural evolution of the Himalaya, and in particular noted the difficulties in using the strain compatibility requirement in real geologic settings, mainly because of the poorly resolved contribution of faulting to the overall deformation. Martin Burkhard used the results of strain studies in the Helvetic Alps to show that the nappes had been affected by a two-phase history involving transport-parallel extension during nappe emplacement and orogen-parallel extension after emplacement. His talk highlighted the problems associated with explaining orogen-parallel extension. Gautam Mitra reviewed the current status of strain studies across the Idaho-Utah-Wyoming thrust belt, emphasizing implications for balancing cross-sections and for mechanic models. He showed that cleavage fabrics generally predated thrust faulting, indicating that ductile strain mechanisms were active in the foreland and produced significant strains before the rocks were incorporated into the thrust wedge.

The sixth session, "Brittle Strain Associated with Faulting", focused on methods for estimating the amount of "strain" that discrete brittle faults contribute to the overall deformation. Randall Marrett discussed the observations and theoretical basis for the scaling relations that have been developed for fault populations. He showed how these relationships can be used to estimate the geometric moment tensor, which provides a measure of the bulk strain due to slip on a network of faults. Trenton Cladouhos showed how the geometric

moment tensor could be extended to provide an approximate estimate of brittle strain for large-slip faults, with examples from the San Andreas fault and the Andean thrust belt. Chris Scholz examined some of the physical processes that might be responsible for the observed scaling relationship for faults. He then summarized the results of some recent studies on the relationship of fault size to net slip which indicate that slip on small faults probably accounts for a much smaller proportion of the total brittle strain within a network of active faults than previously thought.

The objective of the seventh and last session, "Use of Strain in Computational Models", was to see how strain data might be combined with geodynamic modeling. Sean Willett presented the results of finite-element modeling of large deformation in a contractional Coulomb wedge, with a special emphasis on how instantaneous strain, κ_N , and finite strain varied within a deforming wedge. Julia Morgan presented the results of a numerical study in which the finite strain in deformed sediments from the toe of the Nankai accretionary wedge was determined using changes in bedding thickness and porosity, as observed in a multi-channel seismic reflection profile. Ian Duncan reviewed the advantages and problems associated with use of the finite-element method for deformational modeling.

The conference provided an important opportunity to assess the current state of strain-analysis research. There were four topics that generated considerable interest and debate: (1) the concept of general shear and the use of κ_N as a generalized descriptor of internal vorticity in deforming rocks; (2) the magnitude of volume strain, and in particular mass loss, in deformed rocks; (3) the determination of brittle strain, that is the bulk strain due to faulting, and how it compares with strain accumulated by ductile processes; and (4) the potential to incorporate strain data in geodynamical models. We view these developments as an indication that strain analysis is taking on a greater importance, both in structural geology and also in other fields such as petrology (mass transfer and volume strain), geodynamical modeling, and seismology.

In closing, we would like thanks the conference participants; their enthusiasm and stamina through a very tightly scheduled meeting made the experience very stimulating and rewarding for us. Special thanks are also due to Lois Elms for her assistance in organizing

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Penrose Conference Participants

Jay Ague
David Anastasio
Edward Beutner
Frank Bilotti
Mark Brandon
Roland Bürgmann
Martin Burkhard
Karen Carter
Trenton Cladouhos
Brooks Clark
Kevin Corbett
Brent Couzens
Darrel Cowan
Jean Crespi
Sandy Cruden
Declan De Paor
Ian Duncan
Terry Engelder
Eric Erslev
Jeffrey Feehan
David Ferrill
Donald Fisher
John Fletcher
Norman Fry
Arthur Goldstein
Norman Gray
Giovanni Guglielmo, Jr.
Jim Handschy
Ron Harris
Jack Henderson
Mariette Henderson
Angela Jayko
Kyuichi Kanagawa
Hermann Lebit
Richard Lisle
Catalina Luneburg
Randall Marrett
Mark McNaught
Win Means
Gautam Mitra
Julia Morgan
Charles Onasch
Cees Passchier
Scott Paterson
Arnaud Pecher
John Ramsay
Nicholas Rast
Robert Ratliff
Lothar Ratschbacher
Stephen Reynolds
Carl Richter
Uwe Ring
Pierre Robin
Chris Scholz
Fried Schwerdtner
Eli Silver
John Stamatakos
Bryan Tapp
Christian Teyssier
Basil Tikoff
Ken Tillman
Othmar Tobisch
Ron Vernon
Simon Wallis
David Ward
John Weber
Ruud Weijermars
Sean Willett
Michael Williams
Steven Wojtal
Nick Woodward
Tom Wright