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Preface

Fabric, Strain and Structural Development in Three Dimensions

The collection of papers of this special issue is an outcome of a Geological Society of America Penrose Conference on ‘Three-dimensional flow, fabric development and strain in deformed rocks and the significance for mountain building processes: new approaches’, held at Monte Verita in Switzerland (Fig. 1) on August 18–24, 2002. In addition to providing a forum for discussing state-of-the-art developments in structural geology, the conference also served to honor John G. Ramsay, who has had such a huge impact on the field of structural geology and made major contributions to the state of knowledge on the theme of the conference and the structures of the mountain belt where the conference was held. A selected bibliography of John’s work appears at the end of this introduction.

During the past decade or so, research in structural geology has benefited tremendously from the development of technologies that refine our ability to describe fabrics and structures and provide sophisticated tools to allow analysis of rock deformation on all scales. Such technologies include electron microscopy, which allows elucidation of deformation mechanisms on the grain and sub-grain scales. On a much larger scale, they include space borne geodesy, which allows direct monitoring of regional displacements of crustal blocks and continents. In addition, the exponential growth of computational power now allows realistic simulations of deformation processes and structures at any scale.

Our current understanding of rock deformation and development of structures and fabrics is perhaps too strongly biased by traditional kinematic and mechanical models, most of which are based on two-dimensional, symmetric representations and steady-state flow. Structures and fabrics in naturally deformed rocks, on the other hand, often lack high-order symmetry and the rocks in which they develop appear to have followed rather complicated deformation paths, as a result of spatial or temporal variability of the component deformation processes. This fact, together with the availability of increasingly sophisticated tools for analysis of structures and fabrics, provided the impetus for the conference and the substance of many of the papers in this special issue.

An example of the complexity of three-dimensional deformation is afforded by the superposition of structures during multiple deformation episodes or progressive deformation of a complex nature. In non-coaxial folding, later generation folds are highly variable in orientation, as they form on curviplanar surfaces and layers produced by earlier folding. Though we are able to analyze the geometries of fold interference patterns, it remains enigmatic how fold formation operates along curviplanar surfaces. In terms of fold mechanics complications arise, for example, in that the layer-parallel shortening component associated with the initiation of buckling continuously changes in magnitude due to variable layer orientation relative to the bulk deformation. Field observations indicate that in such situations non-cylindrical fold morphologies develop; it requires a three-dimensional approach to describe completely the development of such folds in the context of the bulk deformation field. This is a challenge using a forward approach to structural analysis, but it is equally challenging if an inverse approach is taken. Such an approach is desirable in tectonic analysis, with the objective of using individual folds or other structures in fold interference systems to provide direct information on the bulk deformation and its history (i.e. kinematics). This is not straightforward because local folds (and associated structures) are the response of the imposed deformation to the *local* conditions. Pre-existing folds become reoriented and modified in complicated ways depending on the local character of the imposed deformation. Structural analysis in such systems is therefore scale dependant, with the consequence that a series of deformation events elaborated at one outcrop, or domain, is spatially and/or temporally not necessarily congruent with the deformation cycles found at another outcrop or domain. The key to successful tectonic analysis is knowing and taking into account the scales of wavelengths of the deformations involved.

The papers in this special edition cover a good part of the range of topics discussed at the conference.

Jones, Holdsworth, McCaffrey, Clegg and Tavarnelli treat the scenario of three-dimensional non-coaxial deformation caused by plate motions oblique to plate margins. They argue that deformation is accommodated by displacement on interconnected arrays of faults on several scales, with fault domains tending to follow the orogenic grain. The faults allow deformation partitioning and produce crustal anisotropy. Strain within domains need not represent the bulk strain at the plate scale. The partitioning of distributed

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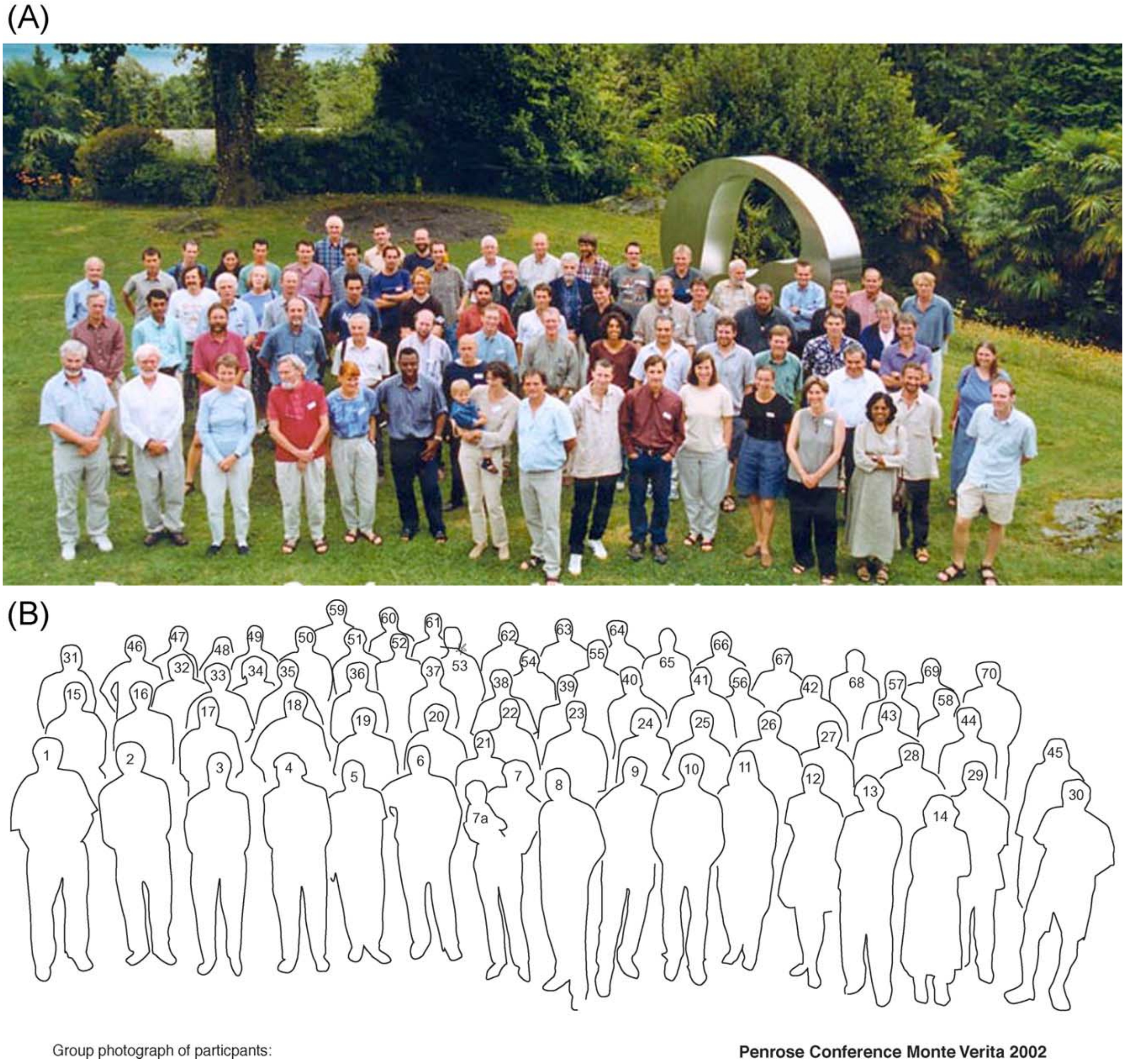

Fig. 1. Attendees of the Geological Society of America Penrose Conference at Monte Verita, Switzerland. Participants in alphabetic order (numbers refer to (b)): Jeff Amato (10), Chuck Bailey (39), Michael Bestmann (21), Shamik Bose (16), Mark Brandon (18), Margaret Brewer (*), Jean-Pierre Burg (67), Martin Burkhard (29), Luigi Burlini (*), Noel, Canto-Toimil (36), Jordi Carreras (20), Dyanna Czeck (45), Jean Crespi (12), Hagen Deckert (52), Declan DePaor (44), Allen Dennis (57), John Dewey (*), Dorthee Dietrich (5), David Durney (33), Mike Edwards (53), Carol Evenchick (*), Paul Evans (30), Raymond Fletcher (15), Klaus Gessner (*), Art Goldstein (69), Albert Griera (38), Djodje Grujic (46), Tekla Harms (13), Robert Hatcher (62), Reneé Heilbronner (3), Christoph Hilgers (61), Christopher Holms (26), Eric Horsman (*), David Hood (9), Peter Hudleston (55), Zeshan Ismat (24), James Jackson (59), Richard Jones (68), Paul Karabinos (43), Richard Ketcham (40), Sergio Llana-Funez (51), Richard Law (70), Hermann Lebit (8), Bernd Leiss (65), Richard Lisle (63), Catalina Lüneburg (7) and Adrian (7a), Neil Mancktelow (27), Micheal Maxelon (37), Gautam Mitra (25), Alison Ord (58), Fernado Ornelas (49), Cees Passchier (*), Terry Pavlis (17), Jeffrey Rahl (22), John Ramsay (4), Ernest Rutter (1), Stefan Schmalholz (50), Stefan Schmid (31), Sudipta Sengupta (14), Carol Simpson (34), Athur Snoke (54), Gary Solar (42), Aaron Stallard (60), Aviva Susman (48), Jean Pierre Tschouankoue (6), Michael Terry (56), Basil Tikoff (32), Jens Walter (66), John Watkinson (2), Matthias Weger (28), Rami Weinberger (47), John Wheeler (35), Robert Wintch (41), Christine Witkowski (11), Steven Wojtal (23), Adolph Yonkee (64), Ivan Zagorchev (19). * Refers to participants not present on the picture.

and discrete deformation in mountain belts is addressed more explicitly in the paper of Horsman and Tikoff, who present a method for quantifying bulk deformation and bulk kinematics by combining the displacement fields of discrete (e.g. fault) and distributed (e.g. shear zone) components, noting that the distinction between distributed and discrete deformation is scale-dependent. The degree of non-coaxiality can be estimated by vorticity analysis. Merschat, Hatcher and Davis use the Inner Piedmont region of the Southern Appalachians as a case study to estimate three-dimensional crustal flow in a mountain belt. Field studies and estimates of bulk strain and kinematics indicate a curved pattern of crustal scale transport and flow, which can also be seen by map scale sheath folds and mineral lineation patterns. The authors conclude that this three-dimensional flow pattern is caused by transpression. Another regional case study is provided by Yonkee, who describes the distribution of deformation in the Willard thrust sheet of the Idaho–Utah–Wyoming thrust belt. The sheet is 10–15 km thick and has been transported about 50 km. Strain depends on the level within the sheet and lithology and involves thrust-parallel shear and variable minor thrust-parallel extension or shortening. Strain increases towards the base of the sheet, and is associated there with minor folds and cleavage. The kinematic pattern reflects a very weak basal fault zone and a higher strength upper part. In another case study, but on an outcrop scale, Evins and Laajoki show that inclusion trails within equant garnets in Precambrian pelitic rocks in Finland reflect microfolding and warping of foliation prior to the development of later folds and shear zones. The inclusion trails show no consistent variation with respect to the later structures, which are interpreted to have formed in overall pure shear, during which the garnets did not rotate.

Another suite of papers examines the development of structures in complex deformational settings. The morphological alterations of folds during refolding events are investigated by Sengupta, Ghosh, Deb and Khan who describe, on the basis of numerical modeling and analogue experiments, how earlier folds can either tighten or open out during superposed deformation. Opening out occurs by external layer rotation and homogeneous strain, when the bulk extension is perpendicular to the F1 axial plane. Nearly isoclinal or tight folds do not open out and remain tight after deformation. The rate of opening changes with progressive deformation. Carreras, Druguet and Griera investigate different types of folds and their kinematic significance in localized shear zones affecting rocks possessing an earlier tectonic fabric and structures. Folds can be pre-existing and modified by later shear or formed during the shearing. The final fold geometry depends on the vorticity of flow within the shear zone, the rheology and the initial orientation of the folded surface. Shear zone-related folds show a complex relationship with the kinematic frame and are therefore ambiguous kinematic indicators. Taking a novel theoretical approach, Patton and Watkinson analyze the behavior of compressed stratified layers represented by second order fluids, which exhibit non-linear viscoelastic effects. Scaling and non-dimensionalization of the model reveals the significance of the Weissenberg number, which relates the ratio of viscous strain ratio to relaxation time of normal stresses. It is the contrast in relaxation time between layers that drives the amplification of instabilities rather than the rheological contrast. The model provides an explicit transition from distributed to localized deformation (faulting) and predicts folding non-dimensional wavelengths of 3–7 and faulting at wavelengths of about 7. Also, taking a theoretical approach, Fletcher analyzes the initiation of cylindrical structures by buckling (in shortening) or necking (in extension) in an anisotropic power-law fluid under general plane flow, where the initial anisotropy is comparable with a pre-existing foliation. The model predicts the development of band structures simulating crenulations and internal boudinage; with linear fluids resulting in upright folds or crenulations and non-linear fluid leading to conjugate structures. Growth rate is independent of wavelength and, for chevron folds, independent of power-law exponent.

The last two papers in this special issue are dedicated to novel techniques in rock fabric analysis and the micromechanical behavior of minerals during deformation. Llana-Fúnez and Rutter take an experimental approach to investigate non-plane strain flow geometries using axisymmetric compression of short cylinders of Solnhofen limestone. Shape and crystallographic preferred orientations of calcite, measured by EBSD, are used to determine non-plane strain flow geometries within the specimen, and they record a change in orientation of stretching direction. The non-coaxial flow component is indicated by extrusion of the middle part of the samples as shortening progresses. A new method of fabric analysis is presented by Ketcham, who uses high-resolution X-ray computed tomography (HRXCT) to image the interior of rocks in three dimensions in a non-destructive way. This method allows quantifying of the location, size, shape, and orientation of individual crystals, and their contacts with adjacent objects. It also allows performance of a more general fabric analysis on any distinguishable component in a sample and calculation of a fabric tensor to determine degree of anisotropy and shape indices without destroying the sample.

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Selected Bibliography; John Graham Ramsay

Ramsay, J.G., 1958. Superposed folding at Loch Monar, Inverness-shire and Ross-shire. Quaternary Journal of the Geological Society London 113, 271–308.

Ramsay, J.G., 1960. The deformation of early lineation structure in areas of repeated folding. Journal of Geology 68, 75–93.

Ramsay, J.G., 1962. The geometry of conjugate folds systems. Geological Magazine 99, 516–526.

Ramsay, J.G., 1962. Interferance pattern produced by the superposition of folds of similar type. Journal of Geolgy 70, 466–481.

Ramsay, J.G, 1963. Structures and metamorphism of the Moine and Lewisian rocks of the North-West Caledonides. In: Johnston, Stewart, F. (Eds.), The British Caledonides. Oliver & Boyd, Edinburgh, pp. 143–175.

Ramsay, J.G., 1967. Folding and Fracturing of Rocks. McGraw Hill, New York (Translations into Spanish, 1977 and Chinese, 1986).

Ramsay, J.G., 1969. The measurement of strain and displacement in orogenic belts. In: Kent, P.E. et al. (Ed.), Time and Place in Orogeny Special Publication, 3. Geological Society, London, pp. 43–79.

Ramsay, J.G., 1974. The development of chevron folds. Geological Society of America Bulletin 85, 1741–1754.

Ramsay, J.G., 1976. Displacement and strain. Philosophical Transactions of the Royal Society of London 283, 3–25.

Ramsay, J.G., 1980. The crack-seal mechanism of rock deformation. Nature 284, 135–139.

Ramsay, J.G., 1980. Shear zone geometry: a review. Journal of Structural Geology 2, 83–89.

Ramsay, J.G., 1982. Rock ductility and its influence on the development of tectonic structures in mountain belts. In: Hsü, K. (Ed.), Mountain Building Processes. Academic Press, London, pp. 111–127.

Ramsay, J.G., 1989. Fold and fault geometry in the Western Helvetic nappes of Switzerland and France and its implication for the evolution of the arc of the Western Alps. In: Coward, M., Dietrich, D., Park, G. (Eds.), Alpine Tectonics Geological Society Special Publication 45, pp. 33–35.

Ramsay, J.G., 1997. The geometry of a deformed unconformity in the Caledonides of NW Scotland. In: Sengupta, S. (Ed.), Evolution of Geological Structures. Chapman & Hall, London, pp. 445–472.

Ramsay, J.G., Allison, I., 1979. Structural analysis of shear zones in an alpinised Hercynian granit, Maggia Lappen, Pennine Zone, Central Alps. Schweizerische Mineralogisch Petrographische Mitteilungen 59, 251–279.

Ramsay, J.G., Graham, R.H., 1970. Strain variation in shear belts. Canadian Journal of Earth Sciences 7, 786–813.

Ramsay, J.G., Huber, M.I., 1983. The Techniques of Modern Structural Geology, Volume 1: Strain Analysis. Academic Press, London (Chinese Translation, 1991).

Ramsay, J.G., Huber, M.I., 1987. The Techniques of Modern Structural Geology, Volume 2: Folds and Fractures. Academic Press, London (Chinese Translation, 1991).

Ramsay, J.G., Lisle, R.J., 2000. The Techniques of Modern Structural Geology, Volume 3: Applications of Continuum Mechanics to Structural Geology. Academic Press, London.

Ramsay, J.G., Wood, D., 1973. The geometric effect of volume change during deformation processes. Tectonophysics 16, 263–277.

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