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Editorial

An introduction to the Tectonophysics special issue "Into the deformation history of folded rocks"

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Geomechanical modeling

1. Introduction

Folding is a nearly universal mode of deformation of rocks. From the meso-scale to the regional scale, within poorly lithified sediments or metamorphic nappes, folds widely occur in mountain belts, but also in extensional settings. However, depending on P–T conditions and rheology, mechanisms of folding may greatly differ.

In thrust belts and orogenic forelands, fold evolution has been for a long time mainly described in terms of geometry and kinematics (e.g. Buxtorf, 1916; Chamberlin, 1910; Dahlstrom, 1969; Erslev, 1991; Jamison, 1987; Rich, 1934; Suppe, 1983). Since the late 60s, other lines of work have focused on the deformation mechanisms that accommodate internal strain within folded rocks (e.g. Ramsay, 1967). More recent studies have focused on syn-folding deformation pattern at the meso-scale (fractures, solution seams: e.g., Fischer and Jackson, 1999; Hancock, 1985; Salvini and Storti, 2001; Stearns, 1968; Storti and Salvini, 1996; Tavani et al., 2011) and at the micro-scale (mechanical compaction, pressure-solution, intragranular deformation: e.g., Allmendinger, 1982; Amrouch et al., 2010; Hedlund et al., 1994; Soto et al., 2003), on the evolution of paleostress magnitudes within folded strata (e.g., Amrouch et al., 2011) and on the changes in Pressure–Temperature–Chemistry (P–T–X) conditions during folding (e.g. Beaudoin et al., 2011; Bradbury and Woodwell, 1987; Evans, 1995; Srivastava and Engelder, 1990; Travé et al., 2000). These factors all together strongly control rock mechanical properties and reservoir quality.

However, the changes in P–T–X conditions and the stress and strain pattern within folded strata remained to be more properly linked to the geometric/kinematic macroscopic evolution of folds. In addition, to become more realistic and predictive in terms of onset of failure, type, abundance and variability of deformation features as well as orientations and magnitudes of stresses in folded strata, numerical models of folding were required to evolve from purely kinematical toward more mechanical. During the last two decades, a lot of work has been carried out on these topics and new exciting results are currently being obtained which will undoubtedly help improve our understanding of folded rock deformation processes and history. Advances on such subject are fundamental nowadays, with important socio-economic implications, since accurate description and simulation of geological reservoirs for resources (e.g. hydrocarbons, water) or waste (e.g. CO_2, radioactive waste) require a good knowledge of the mechanical behavior of rocks when they are folded and fractured.

Following a successful session at the EGU Vienna Meeting in 2011, this Tectonophysics Special Issue aims at making the point on our understanding of the relationships between the folding process, the development in time and space of fold-related meso- and microstructures, the orientations and magnitudes of stresses and the fluid flows within fractures and faults during fold development. Of particular interest to that respect is the promising comparison of the type, distribution and sequence of macro- and meso-scale (i.e., sub-seismic) deformation features revealed by field observations in well-exposed folds, of the orientations and magnitudes of stresses and finite strain derived from petrophysical and paleopiezometric laboratory analyses and of the results of geomechanical models of folding that use realistic rheologies for rocks and take into account mechanical stratigraphy, inherited discontinuities and bedding-slip surfaces.

2. Content of the volume

The volume is divided into five chapters.

2.1. Stress and strain within folded strata (1): a view from fractures and faults

Quinta and Tavani analyze fracture and fault pattern using fieldwork and aerial images in order to unravel the tectonic history of the south-western Basque-Cantabrian Belt (Spain). On the basis of a structural and microstructural study of the Rattlesnake Mountain anticline (Wyoming), *Beaudoin et al.* reconstruct the kinematic evolution of Laramide basement-cored folds together with the Sevier and Laramide orogenic stress build-up in the Bighorn Basin. *Reif et al.* describe fracture patterns in the Kurdistan Region of Iraq, a poorly accessible and unexplored area of the Zagros, and show that this pattern comprises pre-folding and fold-related fractures which are related to the kinematic evolution of the thrust belt. A striking result of these three studies is that a large part of the meso-scale structures (i.e., fractures) have formed during the early stages of orogenic deformation before significant folding and thrusting, and even in the pre-orogenic stages (e.g., during earlier compressional events or foreland flexure-related extension).

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2.2. Stress and strain within folded strata (2): a view from microstructures and rock physical properties

Robion et al. reconstruct the evolution of deformation in the Corbières fold-thrust belt (Sub-Pyrenean Zone) by combining a structural analysis and a study of magnetic fabric and of anisotropy of physical properties of rocks.

2.3. Fold kinematics and role of mechanical stratigraphy

Ferrill et al. challenge the usual interpretation of drag folds as the product of frictional sliding along a fault and progressive tilting of beds with increased amount of displacement and show that fault-tip folding in mechanically layered rocks can produce synthetic dip (drag) early in the fault development history prior to propagation of the fault tip through the folded layer. *Exposito et al.* analyze the variations in the structural style and the emplacement mechanisms of the fold- and thrust belt in the Western Gibraltar Arc and demonstrate that these variations are mostly controlled by the primary rheology of both rock units and decollement levels, as well as by the structural position of the tectonic units in the orogenic pile.

2.4. Fluid flow and evolution of P–T–X conditions within folds

Evans et al. document dynamic changes in fluid pressure, temperature and chemistry during folding on the basis of fluid inclusion microthermometry and stable isotope analyses of vein minerals in the Patterson Creek anticline (Central Appalachians); they show that these changes result from variations in fracture connectivity and fluid communication between stratigraphically restricted fluid reservoirs. On the basis of an integrated study of sedimentary facies, diagenesis, fracture stratigraphy, stable isotope analyses of vein cements and fluid inclusions microthermometry, *Barbier et al.* demonstrate the impact of folding and fracturing on the paleo-hydrogeological evolution of the Laramide Sheep Mountain and Rattlesnale Mountain basement-cored anticlines (Wyoming); they especially emphasize the role of the vertical connectivity of fractures which can be acquired at various stages of folding, depending on the initial sedimentary succession, and its later diagenetic and structural evolution.

2.5. Geomechanical modeling of folding

By using finite element models with a critical state mechanics constitutive rule, *Albertz and Lingrey* illustrate how variable mechanical stratigraphy, initial fault dip and inter-layer detachments affect the way thrusts propagate and thus exert a significant control on resultant fold layer geometry. The companion paper by *Albertz and Sanz* analyzes the plastic strain and the stresses derived from the previous models for a variety of fold geometries and kinematics and illustrates how geomechanical information improves our understanding of the mechanics of fault-related folding. In a similar way, *Smart et al.* use finite element modeling with elasto-plastic rheology to develop forward models of fault-related folds that incorporate realistic fold geometry and mechanical stratigraphy and include faults and bedding-slip surfaces. The comparison of the modeling results in terms of stress and strain with (micro)structural data from the Bargy anticline (northern Subalpine Chain) emphasizes the potential of geomechanical modeling to predict stresses, fractures, and sub-seismic faults in geologic structures. Starting with a 3D restoration of the Laramide Split Mountain anticline (Utah) as initial displacement loading conditions, *Sassi et al.* use the finite element method with a multiplane elasto-plastic constitutive rule representing the fractures to generate realistic fold-fracture models and to constrain the development of fracture patterns within folded strata (including inherited and fold-related fracture sets); depending on the initial fracture configuration, the calculated fracture patterns appear to be markedly different, which may help constrain fractured reservoir characterization when combined with field observations in natural analogs.

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References

Allmendinger, R.W., 1982. Analysis of microstructures in the Meade plate of the Idaho–Wyoming foreland thrust belt, U.S.A. Tectonophysics 85, 221–251.
Amrouch, K., Robion, P., Callot, J.-P., Lacombe, O., Daniel, J.-M., Bellahsen, N., Faure, J.-L., 2010. Constraints on deformation mechanisms during folding provided by rock physical properties: a case study at Sheep Mountain anticline (Wyoming, USA). Geophysical Journal International 182, 1105–1123.
Amrouch, K., Beaudoin, N., Lacombe, O., Bellahsen, N., Daniel, J.M., 2011. Paleostress magnitudes in folded sedimentary rocks. Geophysical Research Letters 38, L17301.
Beaudoin, N., Bellahsen, N., Lacombe, O., Emmanuel, L., 2011. Fracture-controlled paleohydrogeology in a basement-cored, fault-related fold: Sheep Mountain anticline (Wyoming, USA). Geochemistry, Geophysics, Geosystems 12, Q06011.
Bradbury, H.J., Woodwell, G.R., 1987. Ancient fluid flow within foreland terrains. In: Goff, J.C., Williams, B.P.J. (Eds.), Fluid Flow in Sedimentary Basins and Aquifers. Geological Society, London, Special Publications 34, 87–102.
Buxtorf, A., 1916. Prognosen und Befunde beim Hauensteinbasis-und Grenchenburgtunnel und die Bedeutung der letzteren für die Geologie des Juragebirges. Verhandlungen Naturforschende Gesellschaft Basel 27, 184–254.
Chamberlin, R.T., 1910. The Appalachian folds of central Pennsylvania. Journal of Geology 18, 228–251.
Dahlstrom, C.D.A., 1969. The upper detachment in concentric folding. Canadian Society of Petroleum Geology Bulletin 18, 332–406.
Erslev, E.A., 1991. Trishear fault-propagation folding. Geology 19, 617–620.
Evans, M.A., 1995. Fluid inclusions in veins from the Middle Devonian shales: a record of deformation conditions and fluid evolution in the Appalachian Plateau. Geological Society of America Bulletin 107, 327–339.
Fischer, M.P., Jackson, P.B., 1999. Stratigraphic controls on deformation patterns in fault-related folds: a detachment fold example from the Sierra Madre Oriental, northeast Mexico. Journal of Structural Geology 21, 613–633.
Hancock, P.L., 1985. Brittle microtectonics: principles and practice. Journal of Structural Geology 7, 437–457.
Hedlund, C.A., Anastasio, D.J., Fisher, D.M., 1994. Kinematics of fault-related folding in a duplex, Lost River Range, Idaho, USA. Journal of Structural Geology 16, 571–584.
Jamison, W.R., 1987. Geometric analysis of fold development in overthrust terranes. Journal of Structural Geology 9, 207–219.
Ramsay, J.G., 1967. Folding and Fracturing of Rocks. McGraw-Hill, New York.
Rich, J.L., 1934. Mechanics of low-angle overthrust faulting as illustrated by the Cumberland Thrust Block, Virginia, Kentucky and Tennessee. American Association of Petroleum Geologists Bulletin 18, 1584–1596.
Salvini, F., Storti, F., 2001. The distribution of deformation in parallel fault-related folds with migrating axial surfaces: comparison between fault-propagation and fault-bend folding. Journal of Structural Geology 23, 25–32.
Soto, R., Mattei, M., Casas, A.M., 2003. Relationship between AMS and folding in an area of superimposed folding (Cotiella-Boixols nappe, Southern Pyrenees). Geodinamica Acta 16, 171–185.
Srivastava, D.C., Engelder, T., 1990. Crack-propagation sequence and pore-fluid conditions during fault-bend folding in the Appalachian Valley and Ridge, central Pennsylvania. Geological Society of America Bulletin 102, 116–128.
Stearns, D.W., 1968. Certain aspects of fracture in naturally deformed rocks. In: Riecker, R.E. (Ed.), NSF Advanced Science Seminar in Rock Mechanics. : Bedford. Air Force Cambridge Research Laboratory, Massachusetts, pp. 97–116.
Storti, F., Salvini, F., 1996. Progressive rollover fault-propagation folding: a possible kinematic mechanism to generate regional-scale recumbent folds in shallow foreland belts. American Association of Petroleum Geologists 80, 174–193.
Suppe, J., 1983. Geometry and kinematics of fault-bend folding. American Journal of Science 283, 684–721.
Tavani, S., Mencos, J., Bausà, J., Muñoz, J.A., 2011. The fracture pattern of the Sant Corneli Bóixols oblique inversion anticline (Spanish Pyrenees). Journal of Structural Geology 33, 1662–1680.
Travé, A., Calvet, F., Sans, M., Vergés, J., Thirlwall, M., 2000. Fluid history related to the Alpine compression at the margin of the south-Pyrenean Foreland basin: the El Guix anticline. Tectonophysics 321, 73–102.

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