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# Faults, stresses and mechanics of the upper crust: a tribute to Jacques Angelier

Guest editors: OLIVIER LACOMBE[1] and FRANÇOISE BERGERAT[2]

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## IN MEMORIAM: JACQUES ANGELIER (1947-2010)

Jacques Angelier was born 2 March 1947 in Alès, France. He passed away on 31 January 2010. Jacques was a student at 'Ecole Normale Supérieure' of Saint-Cloud from 1966 to 1970. He obtained his PhD in 1970 and his DSc in 1979. From 1970-71 Jacques was assistant lecturer at the University Pierre & Marie Curie in Paris (Paris VI), and from 1971-76 assistant lecturer at the University of Orléans. Following his stay in Orléans, Jacques returned to University Pierre & Marie Curie in 1976 as an assistant professor and, from 1981, as a full professor. Jacques worked in Paris until 2003, then moved to the Oceanological Observatory of Villefranche-sur-Mer, also a part of University Pierre & Marie Curie.

The main research activities of Jacques Angelier were in the fields of structural geology and geodynamics, with focus on brittle deformation. He was a leader in analysing crustal stresses, that is, in developing methods to understand the various stress fields to which the Earth's crust has been subjected through time. The basic techniques are inversion of fault-slip data from minor fault sets measured in the field and of focal mechanisms (fault-plane solutions) of earthquakes in a given area to calculate the state of stress.

Inversion of fault data is primarily used to infer the so-called "paleo-stresses", that is, the state of stress that existed in the past at the time of fault slips. This method relies much on measurements and interpretation of striations on fault planes in the field. Focal mechanisms of earthquakes are used to infer current stresses in active fault zones. Jacques developed computer programs to calculate the stress tensors from these various types of data.

Jacques Angelier applied his methods to carry out regional and local brittle-tectonic studies in many countries and regions. These include North Africa, Greece, Turkey, Mexico, USA, Japan, Korea, Russia, Ukraine, Iran, Canada, Greenland, Taiwan, Iceland and, of course, France.

Since the late 1980's his research focused increasingly on active deformation. This work enabled him to combine field studies of brittle deformation with the analysis of earthquakes, the focus of the latter being on seismotectonics and associated current stress fields. The main targets of his seismotectonic studies were the divergent plate boundary of Iceland and the convergent plate boundary of Taiwan.

The great scientific legacy of Jacques Angelier, his impact on structural geology, in particular on the study of brittle deformation and crustal stresses, has been of first importance and will continue to be so for many years to come (photos 1 to 7).

## INTRODUCTION TO THE SPECIAL ISSUE

It is of course almost impossible to make a complete state-of-the-art on crustal mechanics, and even to summarize all the major steps that led to our present knowledge on this topic. As an introduction to the special issue, we have chosen to focus on 3 aspects Jacques Angelier has worked on during his carrier, and to recall what we think to have been noticeable steps, among many others...

### State of stress in the earth crust

The natural stress field which exists in a rock mass is generated by numerous mechanisms, such as gravitational loading, thermal changes, pore fluid diffusion, elevation differences, and last but not least, tectonics. The motivation to characterize the distribution of stresses in the crust arises from (1) applied geological purposes such as geological hazards (earthquakes, landslides), engineering activities (e.g., stability and safety of underground workings and boreholes) and resource exploration, but also from (2) fundamental geological purposes, such as understanding the mechanical behaviour of geological materials and deciphering tectonic mechanisms at different scales (from the crystal to the plate).

Because (i) the exact geological history of rock masses cannot be known precisely, (ii) the constitutive equations describing the mechanical behavior of rocks remain approximate, and (iii) the detailed structure of a rock mass cannot be determined exactly, it is impossible to evaluate by straight computation the natural stress field. For this reason,

1. Professor at the Institut des Sciences de la Terre de Paris – ISTeP, Université Pierre et Marie Curie
2. Research Director at the Centre National de la Recherche Scientifique (CNRS), Institut des Sciences de la Terre de Paris – ISTeP, Université Pierre et Marie Curie

several techniques have been developed to try to measure or to reconstruct it. Among them, Jacques Angelier has been one of the pioneers in the analysis of the orientation of the slip motions on faults determined either from the observation of slickensides on ancient minor faults or from the focal mechanism of the seismic events. Following first works on the topic [e.g., Carey and Brunier, 1974; Angelier, 1975, 1984; Etchecopar *et al.*, 1981], numerous techniques of fault-slip data inversion for regional stress have been set out and are available for the community [see review paper by Célérier *et al.*, 2012]. The use of fault slip parameters during earthquakes and of earthquake focal mechanisms has also been a major stepforward for the understanding of the contemporary state of stress [e.g., Byerly and Stauder, 1957; Aki, 1968; McKenzie, 1969]. Together with other techniques of *in situ* determination of the state of stress [see review paper by Schmitt *et al.*, 2012], these techniques have provided a large dataset on modern stresses which has been synthetized in the form of two "World Stress Maps" [Zoback *et al.*, 1992; Heidbach *et al.*, 2010], providing new insights into the dominant stress sources at different scales in the lithosphere. To what extent paleostresses can be compared to modern stresses in terms of physical and geological meaning still remains a matter of debate [see discussion paper by Lacombe, 2012].

### Fracture and fault mechanics

Fractures and faults are amongst the main features of the deforming upper crust. They have been used for a long time as reliable records of larger scale tectonics [e.g., Mattauer and Mercier, 1980] and understanding their initiation has been (and is still) the purpose of many works over at least the last two centuries [e.g., Pollard and Aydin, 1988]. Jacques Angelier was interested in this topic: although he focused more on geometrical and tectonic aspects than on true mechanical aspects, he for instance investigated effective tension-shear fractures relationships, especially in extensional settings (Suez, Iceland).

Early concepts on the mechanics of fracturing and faulting indeed date back to the 18$^e$ [e.g., Amonton, 1699; Coulomb, 1776; Daubrée, 1879; Mohr, 1900; Anderson, 1905; Griffith, 1924]. Coulomb [1776] developed his failure criterion by assuming that slip along any internal plane within a material was impeded by both cohesion and an internal friction, and showed that failure/yield strength is pressure sensitive. Griffith [1924] addressed the problem of quasi brittle fracture/rupture based on the so-called Griffith energy balance criterion that defines the stability condition of the preexisting crack the propagation of which leads to rupture. An alternative view of the failure of materials considers fracture/rupture as resulting from a constitutive (or material) instability, which leads to the deformation bifurcation and to the formation of localization bands [e.g., Rice, 1973]. As soon as in 1905, Anderson proposed, on the basis of experimentally deformed intact rocks, that the directions of the principal stresses can be determined from a set of conjugate faults. Frictional sliding along a preexisting plane of weakness in an otherwise homogeneous material was also investigated and was shown to be possibly modeled by a Mohr-Coulomb criterion [e.g., Jaeger, 1959, 1960; Sibson, 1985]. Byerlee [1978] demonstrated also on the basis of laboratory tests that the sensitivity of strength to pressure is constant for nearly all kinds of pre-cut rocks, thus opening the way to the extension of his criterion to the pre-fractured brittle upper crust (the so-called Byerlee's rule). Among recent ways of fracture mechanics studies is the consideration of the entropy evolution of rock-fracture networks which may provide a basis for a better understanding of the energy input needed for fracture propagation and associated strain during earthquakes or volcanic eruptions.

At a larger scale, fault zones control a wide range of crustal processes. Although they occupy only a small volume of the crust, fault zones have a controlling influence on the crust's mechanical as well as fluid flow properties [see review paper by Faulkner *et al.*, 2010]. Crustal stress magnitudes at shallow crustal levels appear generally to be limited, and even controlled, by the frictional strength on well-oriented faults (state of failure equilibrium). Such critically stressed faults maintain high fluid permeability, hence hydrostatic fluid pressure, within the upper seismogenic crust [Townend and Zoback, 2000]. Expected new developments concern the better characterization of crustal-scale fault zones in terms of internal structure and fluid-rock interactions, localization of shear strain as well as consideration of a realistic (e.g., elasto-plastic) rheology to describe their long-term behavior.

### Active tectonics, seismic rupture and fault dynamics

Jacques Angelier also addressed the problem of the short-term behavior of active faults (locked vs creeping), for instance by studying the seismogenic Longitudinal Valley fault in eastern Taiwan by means of geodetic surveys and creep-meter analyses. He also addressed the kinematics of active normal and strike-slip faults in Iceland.

Significant steps toward a better characterization of short-term crustal deformation related to faulting involved the use of interferometry [e.g., Massonet *et al.*, 1993] and geodetic survey (GPS) [see review paper by Segall and Davis, 1997]. GPS surveys allowed estimates of the size of locked zones along faults as well as identification of the lack of slip in zones of seismic gap and the record of aseismic slips in subduction zones [e.g., Dragert *et al.*, 2001], which are often associated with non-volcanic tremors recorded by seismological networks. Another input of GPS in seismology is the ability to record low frequency ground motions.

Recent works also revealed the complexity of the seismic source and of the surface slip of major subduction earthquakes (e.g., patches characterized by velocity weakening thus favoring seismogenic slip surrounded by zones in velocity strengthening favoring aseismic slip during post- and interseismic periods), the link between fault slip distribution and fault roughness, the possible occurrence of supershear seismic rupture and the recent identification of pre-earthquake tremors [e.g., Bouchon *et al.*, 2008, 2011]. Recent ways of investigation concern ionospheric seismology and development of a spatial seismometer.

## CONTENT OF THE VOLUME

This thematic issue gathers some of the contributions that were presented in the meeting "Faults: Why? Where? How?" held in the University Pierre et Marie Curie in November 2011. This meeting was organized under the patronage of the French Academy of Sciences, the Pierre & Marie Curie University (UPMC) and the French Geological Society, with the financial and logistic support of the Taiwan National Science Council, GeoAzur (Nice) and ISTeP (Paris) geological departments, the Pierre & Marie Curie University (UPMC), the international Laboratory ADEPT and TOTAL (photos 8 and 9)

This meeting provided the opportunity to re-assess our knowledge on faults, from a regional point of view as well as in terms of their geometrical, kinematical and mechanical analyses. Many contributors of the present issue are his former students (belonging to his school of "brittle tectonics and paleostress analysis"), colleagues and friends from Taiwan, Iceland, Korea, Russia, UK and France. The contributions reflect a large part of the scientific legacy of Jacques Angelier: the topics of the articles range from primarily field-based tectonic studies to primarily theoretical studies of crustal stresses and paleostresses, as well as on crustal mechanics and rheology.

The volume is divided into five chapters.

### Stresses and paleostresses in the earth crust (1): methods

**Lisle** [2013] addresses the common assumption in fault-slip data inversion for stress that slip on faults occurs in the direction of maximum resolved shear stress (Wallace-Bott hypothesis) by examining different situations in relation to the appropriateness of this assumption. He recommends caution with slip data taken from highly curved faults, corrugated faults, lineated portions of stylolitic surfaces, fault systems with bends and flexural slip folds and points out that the assumption may not be valid in a strict sense for reasons of stress heterogeneity, fault interactions and the fault's strength anisotropy, although this difficulty can possibly be circumvented by collecting a sufficient amount of fault-slip data.

The article by **Etchecopar *et al.*** [2013] deals with borehole images for assessing present day stresses. A new processing and filtering method is proposed for identifying stress-induced features and measuring precisely their geometry, and examples are given in Algerian reservoirs: Timimoun, Hassi Messaoud. The paper thus focuses on the morphology of fractures observed and on critical analysis of the images. The combination of observations in multiple deviation situations may lead to a clear stress state definition. Thus, this article presents a great practical interest: once the stress tensor parameters are clearly identified, it becomes possible to predict borehole or perforation stability for any well deviations.

**Maury *et al.*** [2013] discuss the commonly-used methods for inverting earthquake focal mechanisms for stress orientation, especially the physical assumptions and the error determinations, and finally propose an extension for one of the methods. The authors apply the fourth methods for evaluating the stress field in the upper Rhinegraben, based on the Sierentz earthquake (1980) data recorded by a temporary network. They demonstrate that, depending on the methods used, differences in principal stress directions may reach up to 28$^{o}$ and that values of the R factor, characterizing relative differences between principal stress magnitudes, range between 0.3 and 0.7. They conclude on the lack of resolution for the evaluation of the stress field at depth and on the proper attention, which has to be given to the event independence hypothesis.

In their paper, **Rebetsky** and **Tatevossian** [2013] address some problems of earthquake source mechanics by reporting results of stress state reconstruction based on the method of cataclastic analysis of discontinuous dislocations in some seismotectonic active regions. Using the Sumatra, Tokachi-oki and Chile strong earthquakes as case studies, they emphasize common features of the stress state in areas of preparation of strong earthquakes, especially that the distribution of the effective isotropic pressure and of the maximal shear stress in areas of earthquake source preparation is heterogeneous and that the main part of the source is always associated to crustal domains under low effective confining pressure. It is further demonstrated that the rupture usually propagates from the region of high stress gradients toward crustal domains characterized by low effective compression.

### Crustal mechanics and rheology

**Porjesz** and **Bergerat** [2013] address the challenging question of the number of intact rock samples submitted to laboratory tests needed to reliably derive physical properties of *in situ* rock mass, i.e the validity of the extrapolation of the parameters from centimetre scale to a large rock mass. They investigate the scale effects and the influence of discontinuities on the physical properties of the Campanian chalk of Bougival (France). By conducting geophysical investigations on pillars of an underground quarry and rock physics experiments on samples, they show that the presence of discontinuities (fractures, flints) has a major impact on the elastic properties (dynamic Young's modulus and Poisson's ratio) whereas neither the size of the samples nor the overburden rock thickness seem to significantly influence these mechanical properties.

**Le Pourhiet** [2013] first describes in detail the analytical solution for the strain softening model associated to Mohr-Coulomb non associated elasto-plastic flow rule. She then presents results for the formation of shear bands and the related decrease in stress in materials exhibiting a Mohr-Coulomb yield stress, focusing especially on the so-called structural softening. A discussion on the possible shear band angles for the considered Mohr-Coulomb material is also included, emphasizing some differences with previous models where the thickness of the shear bands was not taken into account. The application of the semi-analytical results is of great concern for researchers using numerical simulations to study shear bands and strain localization.

The paper of **Gudmundsson** and **Mohajeri** [2013] deals with the relations between the scaling exponents, entropies, and energies of fracture networks. Based on icelandic examples, they demonstrate that there is a power law on fracture-length and show that there is an abrupt change point in the scaling exponent, suggesting that this point relates to the comparatively long and deep fractures changing from tension fractures to normal faults. This paper offers an original approach since the authors apply concept of entropy to fracture network at geological scale, and calculate it showing a strong linear correlation between the scaling exponents and entropies. They finally discuss fracture formation and propagation from view point of energy balance.

### From ductile to brittle deformation

On the basis of a synthesis of field observations and tectonic studies in the northern Cycladic islands (Greece), **Lacombe *et al.*** [2013] discuss the initiation, geometry and mechanics of brittle faulting in exhuming metamorphic rocks that experienced ductile to brittle transition in the footwall of the post-orogenic extensional detachments. The influence of preexisting rheological and structural anisotropy, such as boudinage or precursory ductile or semi-brittle shear zones on the initiation and geometry of brittle faults is emphasized. The study also addresses the kinematics and the mechanics of low-angle normal faults (inherited and newly-formed), the rupture mechanisms operating in foliated metamorphic rocks as well as the significance of paleostress reconstructions in anisotropic rock masses.

**Augier *et al.*** [2013] report field mapping and analyses of brittle faulting in the sedimentary cover of the Almanzora corridor and the Huércal-Overa basins (Spain), as well as a detailed study of the ductile and ductile-brittle deformation in the footwall unit of the Filabres extensional shear zone. Their study reveals that these intramountane basins developed as extensional basins partly during the latest stages of tectonic denudation of the Sierra de los Filabres, then were weakly inverted under a ~N-S to NNW-SSE compression that resulted in the reactivation of normal faults and in a progressive reduction of water exchange with the Atlantic ocean proposed to be directly responsible for the Late Miocene salinity crises.

### Active deformation and seismotectonics

**Allanic** and **Gumiaux** [2013] report direct evidence of seismogenic faults in the Lepontine Dome (Central Alps, Switzerland) previously considered as tectonically quiescent. They identify aligned clusters of microseismic events, which guided further morpho-tectonic investigations that resulted in recognizing marked scarps, perturbation of the drainage system or shift of terminal moraines. Combining seismological, geological and morphological data allows locating four seismogenic faults the kinematics of which was constrained by fault-slip data and focal mechanisms. These new data, which reveal to be coherent at all scales, provide new constraints on the current stress regime going on in the Lepontine Dome and could have implications for future seismic hazard studies.

**Wu *et al.*** [2013] use the Persistent Scatterers SAR Interferometry (PSInSAR) technique to obtain high density deformation map and to estimate the slant range displacement rate (SRD rate) in the Tainan tableland in western Taiwan. Such study in Tainan city, the fourth largest metropolitan area in Taiwan, is particularly important for evaluating the potential seismogenic structures. A striking result is a change in interseismic deformation pattern compared to previous studies investigating the same area from 1996 to 1999, demonstrating that the interseismic deformation in the area is not steady-state and is affected by significant transient deformation, which could have implication on the seismic cycle.

### Stresses and paleostresses in the earth crust (2): applications

The paper of **Bergerat *et al.*** [2013] combines analyses of geothermal measurements, brittle tectonic data and hydrothermal mineralization in the Hvalfjördur geothermal field of Southwest Iceland, an interesting area because deeply eroded and located very close to the active Icelandic rift, thus providing a three-dimensional view of similar elements of old rift and present rift zones. Their combination of various data provides constraints both about the structure at depth and the water circulation. If paleostress analysis indicates a rather complex stress history, most of the geothermal water appears to be conducted by vertical extension fractures located at depth and explaining the abnormal geothermal gradient. The authors propose a model explaining the relationships between the present-day thermal activity and the intrusive styles of the dykes with distance from a volcanic centre.

**Choi *et al.*** [2013] combined the analysis of faulting in terms of paleostresses with rock mechanics data (friction curve deduced from tension fractures on fault planes affected by friction, experimental Mohr failure envelope derived from rock mechanic tests) in order to evaluate the changes of stress magnitudes during the tectonic history of the Gyeongsang basin (Korea). This approach reveals to be powerful to provide bounds on the ancient principal stress magnitudes and to better constrain the geological history of sedimentary basins that underwent a polyphase tectonic evolution, including changes in burial depths.

Using the fold-thrust belt of NW Taiwan as a case study, **Chu *et al.*** [2013] analyse striated micro-faults and other fractures in order to elucidate their relationships with regional folds and thrusts and regional tectonic stress. The observed joint sets likely formed at depth during a pre-folding stage. Later strike-slip faults accompanying thrusting and folding have reactivated these pre-existing joint sets as slip planes. Inversion of fault-slip data for stress reveal two major compression directions, oriented N110-120ºE and N150-160ºE respectively, which sheds light on the debate about paleostress changes during the Taiwan mountain building process. This work also highlights a greater complexity in interpreting joint sets in NW Taiwan than in earlier studies focusing on individual fold structures.

**Homberg *et al.*** [2013] report new geometric, kinematic, sedimentologic and bio-stratigraphic data on faults and faulted formations in order to constrain the Late Jurassic to Early Cretaceous evolution of the Southeastern basin (France). The deformation mechanism in the basin drastically changed in the Jurassic-Cretaceous transition, with the direction of extension rotating from a WNW-ESE to a NNE-SSW direction. Lateral thickness variations of the sequences, redistribution of sediments as well as faulting at various scales are interpreted in terms of an Early Cretaceous tectono-stratigraphic reorganization of the basin, possibly related to the rifting and later opening of the North Atlantic.

PHOTO 1. – Jacques writing in his notebook in the Thingvellir fissure swarm, Iceland, 2006.

PHOTO 2. – Jacques at the Active Collision in Taiwan International Symposium, Taipei, Taiwan, 1995.

PHOTO 3. – Jacques at the restaurant terrace “La Baleine Joyeuse”, in Villefranche-sur-mer, France, 2009.

PHOTO 4. – Jacques measuring a right-lateral strike-slip fault in a Permian dyke, S. Sandby quarry, Scania Sweden, 2005.

PHOTO 5. – Jacques teaching during a French-Taiwanese fieldtrip, Taiwan,1995.

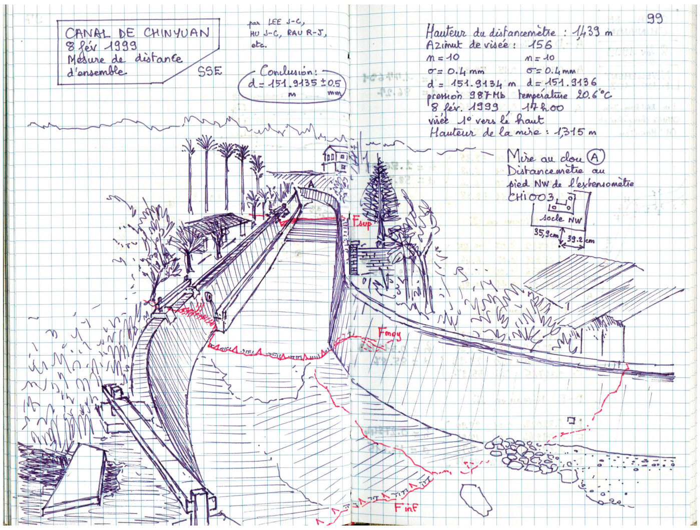


PHOTO 6. – Illustration from a notebook of Jacques, drawn in 1999 and showing a sketch of distance- meter measurements along the Chinyuan canal, Taiwan.

PHOTO 7. – Jacques working with one of his former PhD student (Emmy T.Y. Chang) in the Yuli quarry, Taiwan, 2002.

PHOTOS 8 and 9. – Meeting in the honor of Jacques, held in the University Pierre et Marie Curie, Paris, France, 2011.

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