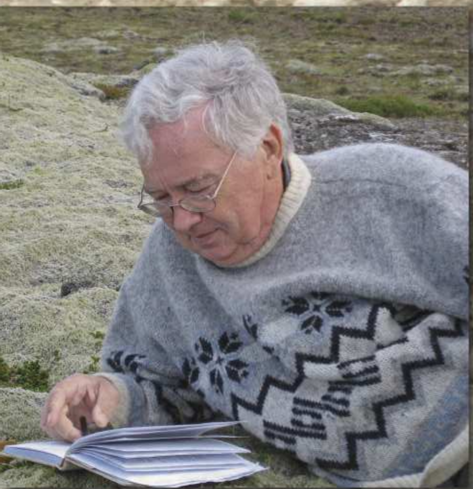
Les failles : pourquoi ? où ? comment ?

Faults : Why ? Where ? How ?



Colloque en Hommage à Jacques ANGELIER
Paris, Jeudi 17 novembre 2011

Meeting in memory of Jacques ANGELIER
Paris, Thursday, november 17th 2011

Résumés

Abstracts

Colloque en Hommage à Jacques Angelier : « Les failles : pourquoi ? où ? comment ? » Jeudi 17 novembre 2011 - Programme

8h00 : Accueil des participants + mise en place des posters
8h30-8h40 : Le mot des organisateurs
8h40-8h50 : *Hommage (B. Goffé, INSU-CNRS)*
8h50-9h00 : *Hommage (Ph. Huchon, ISTeP, et T. Monfret , GéoAzur)*
9h00-9h10 : *Hommage (X. Le Pichon, Académie des Sciences, Président d'Honneur du colloque)*

Session 1 : Sismotectonique et aléa sismique

9h10-9h25 : X. Le Pichon et al. : The northward migration of the Marmara fault
9h25-9h40 : J.C. Lee et al. : Architecture and slip behaviors of a plate boundary mega-thrust: a case study of the longitudinal valley fault system in eastern Taiwan
9h40-9h55 : R. Plateaux et al. : Application of a damped regional-scale stress inversion method: stress field insight around and beneath the Vatnajökull glacier in Iceland

9h55-10h25 : Conférence invitée : Agust Gudmundsson
Thermodynamic aspects of the development of fracture networks.

10h25-10h50 : Session Posters + pause-café

Session 2 : Mécanique des failles et fractures

10h50-11h05 : B. Célérier : Remarks on the relationship between the plunges of the P, B, and T axes of earthquake focal mechanisms and the tectonic regime, the rake of the slip vectors, and the dip of the nodal planes
11h05-11h20 : B. Mary et al. : Temporal and spatial organisation of faulting in frictional wedges.
11h20-11h35 : A. Etchecopar et al. : Borehole images for assessing present day stresses
11h35-11h50 : R. Soliva and F. Maerten : Rupture envelope for fault system reactivation

11h50-12h20 : Conférence invitée : Richard Lisle
A critical look at the Wallace-Bott hypothesis in fault-slip analysis.

12h20-14h20 : déjeuner (Tour Zamansky, 24^{e} étage)

14h20 -14H30 : *Hommage (H.-T. Chu, Taiwan)*

Session 3 : Taiwan

14h30-14h45 : S. Lallemand et al. : Which tectonic regime prevail east of Taiwan ?
14h45-15h00 : J.C. Hu et al. : Present-day crustal deformation in Taiwan orogenic belt from continuous GPS network from 1995 to 2009
15h00-15h15 : J. Malavieille et al. : Impact of surface processes on active faulting in Taiwan

15h15-15h45 : Conférence invitée : François Cornet
On the absence of present day tectonic component in the Paris Basin regional stress field

15h45-16h25 : Session Posters + pause-café

16h25-16h35 : *Hommages (R. Blanchet, J. Aubouin, Académie des Sciences)*

Session 4 : Failles et Géodynamique

16h35-16h50 : T. Derez et al. : Reconstruction of the kinematic evolution in the Queffleuth cataclastic zone of the north-Armorican shear zone, Brittany, France
16h50-17h05 : A. Bertrand et al. : Fault slip analysis and late exhumation of the Tauern window, eastern Alps
17h05-17h20 : C. Pascal et al. : Structure and kinematics of the Møre-Trøndelag fault complex, mid Norway
17h20-17h35 : T. Villemin et al. : Apports de la photogrammétrie à l'étude des champs de fractures actifs en Islande
17h35-17h50 : Y. Rebetsky : Cataclastic analysis method of discontinue displacements and results of tectonophysical analysis of distribution of stress magnitudes in the sources of catastrophic earthquakes

17h50 – 18h15 : *Hommage de la présidence de l'UPMC. (M. Renard). Remise de la médaille de l'UPMC*
18h15-18h30 : Clôture par les organisateurs

Table des matières/Table of contents

KINEMATICS, AGE AND DYNAMIC OF THE BRITTLE DEFORMATION WITHIN THE LEPONTINE DOME (CENTRAL ALPS)

Cécile Allanic [1,2], Christian Sue [2] and Martin Burkhard [†]

[1] Univ. d'Orléans, Université François Rabelais - Tours, CNRS/INSU, Institut des Sciences de la Terre d'Orléans - UMR 6113, 45000 Orléans, France
[2] Univ. de Franche-Comté-CNRS/UMR 6249, 25030 Besançon, France
[†] Deceased

Gneiss domes are ubiquitous features in all exhumed orogens. Their characteristics have been widely investigated in terms of metamorphism and subsequent exhumation to the surface. Here, the recent tectonic regime of the Lepontine dome (Central European Alps) is analyzed with a combination of morphotectonic, structural, and geochronological methods. The new data constitute the first thorough study on the brittle kinematic of the dome and provide new insights into the youngest tectonic evolution of this interesting region near the suture zone between Adriatic and European plate.
Tectonic evolution was determined using fault mapping (by fieldwork and remote sensing) and paleostress inversions (four different coherent methods used). The architecture of the fault pattern reveals a heterogeneous distribution of accidents with a dense relay of dextral strike-slip and normal faults crossing the dome from NW to SE boundaries, thus drawing two horses less dissected. Paleostress inversions confirmed transtensional deformations with few partitioning. Normal tensors are predominant with stable NE-SW $\sigma 3$ axes, coherent with those obtained from strike-slip tensors. Two others minor signal are discussed: a NW-SE extension restricted to the eastern parts of the dome and a N-S extension mainly localized at the north of the dome. Tectonic pseudotachylytes associated with late faults were sampled and dated with $^{40}Ar/^{39}Ar$ methods (step wise heating and in situ laser ablation). All the Ar-Ar analyses are consistent internally and yield total gas ages values between 7.5 and 13 Ma.
Thus, brittle history of the Lepontine dome is dominated by the formation of a double releasing bend under transtensional stress during the late Miocene which follows the emplacement of the gneissic metamorphic core under transpressive conditions. This geodynamical process enhanced the vital part of horizontal movements in plan view (probably driven by the Apulian microplate rotation) and the definitely necessity to construct 3-D lithospheric models to correlate the evolution of different Alpine contemporaneous structures.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

CONTRIBUTION AND LIMIT OF BRITTLE TECTONIC ANALYSES AND PALEOSTRESS STUDIES IN DECIPHERING GEOTHERMAL FIELD FUNCTIONING: THE CASE STUDY OF HVALFJÖRDUR (ICELAND)

Françoise Bergerat[1], Kristjan Saemundsson[2], Loïc Fourel[3] and Jacques Angelier[4]

[1] ISTeP, UMR 7193 CNRS-UPMC, case 117, 4, place Jussieu, 75252 Paris cedex 05, France.
[2] ÍSOR (Iceland GeoSurvey), 9 Grensásvegur, 108 Reykjavík, Iceland.
[3] Imperial College London, South Kensington Campus, London SW7 2AZ, UK.
[4] GéoAzur, UMR 6526 CNRS-UNICE-UPMC-IRD, 06235 Villefranche-sur-Mer, France

The position of Iceland on an active oceanic rift and hot spot provides for high heat flow. High temperature geothermal fields are confined to active volcanoes and their immediate surroundings. Low temperature geothermal fields, which occur throughout the Tertiary and Lower Pleistocene regions of Iceland, play an important economic role in Iceland and are mostly exploited.

The low-temperature geothermal systems are often indicated by the presence of warm or hot springs. In the past two decades many of them have been detected where there was no surface expression. This was the case of the geothermal systems of Hvalfjördur in Western Iceland. We carried out a study of two of the Hvalfjördur low-temperature geothermal fields, based on geological field work, hydro-thermal modelling, stress inversion, analyses of tectonic chronology and hydrothermal mineralisation.

The fields are located in the highly altered core area of a deeply eroded long extinct Pliocene central volcano. No modern geothermal activity related to this volcano occurs. Numerical modelling allowed characterisation of the geometry of anomalies, based on temperature distributions from exploration and production wells, suggesting that, in this case, hot water conveying fractures may be inclined normal faults rather than vertical fissures, which may have major implications for prospection. The brittle tectonic analysis revealed relatively high levels of complexity, with four major trends of extension involving normal and strike-slip faulting modes as well as dyke injection. Relative chronology data analysis indicated that these four regimes were closely intricate in time and space. The most important regime is a NW-SE rift-perpendicular, extension related to the oceanic rifting in Iceland. This trend controls most of the hydrothermal systems found by drilling 50-60m deep wells for thermal gradient measurement in the Hvalfjördur area. Other trends occur also, such as an

E-W rift-oblique extension, producing a N-S trending fracture system with normal faults and veins that show high levels of hydrothermal mineralisation. This N-S trending fracture system has been subject to strong hot water convection, producing a thermal anomaly.

The paleostress analysis provides a mechanical basis to check the consistency of structural hypotheses regarding fracture and fault patterns. Even in a rift environment such as the Hvalfjördur area, that could be expected to be structurally simple, high levels of complexity are present, involving development of several subsets of normal and strike-slip faults with various trends. The structural complexity is due to the presence of the central volcano. Our study showed that the N-S structural trends and the E-W extension are more closely related to the recent hydrothermal activity than the others. Another aspect that deserves attention is the development of NE-SW-striking inclined sheets, dykes and fissures dissecting the Hvalfjördur central volcano. Looking at more recent volcanic areas in southwest Iceland, there are indications that the volcanic systems of the Reykjanes Peninsula extend with their dyke swarms far beyond their surface volcanism with very conspicuous ground fissures into the Pliocene and Early Pleistocene marginal formations. At such large distances, the dykes normally do not reach the surface but the crust responds by fracturing. Pre-existing fractures may be rejuvenated and may thus provide for permeability.

As a case study, it was hoped that this association of different techniques would lead to better understand the kind of secondary permeability that controlled the Hvalfjördur geothermal fields within the frame of rifting in Southwest Iceland. It also might have provided insights regarding both the conductive fracture patterns and the perspectives offered by brittle tectonic analysis to efficiently help geothermal exploration. Both aims could not be convincingly demonstrated. The result of an inclined normal fault as hot water conveying fractures contradicts the drilling results which indicate near vertical water conveying fissures in this case as in some thirty others around the country. Therefore, if the tectonic evolution and the brittle systems are complex, which is the case in Hvalfjördur, the most efficient tool in geothermal prospection remains the shallow geothermal survey, which has proved successful.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

FAULT SLIP ANALYSIS AND LATE EXHUMATION OF THE TAUERN WINDOW, EASTERN ALPS

Audrey Bertrand, Sebastian Garcia and Claudio Rosenberg

Institut für Geologische Wissenschaften, Freie Universität Berlin, Berlin, Germany

The Tauern Window (TW) exposes Penninic basement and its cover units, forming a thermal and structural E-W elongated dome in the core of the Eastern Alps. Located in front of the Dolomite indenter, the TW accomodated the Tertiary exhumation of the Eastern Alps. The western and eastern margins of the TW are delimitated by the Brenner and Katschberg normal fault systems, respectively. The internal structures of the dome are dominated by SW-NE trending upright folds of large amplitude (> 15 km) in the west and more open ones, trending NW-SE, in the east. The presence of extensional structures at the eastern and western margins and large scale upright folds within the TW forms the base of an ongoing debate concerning the exhumation mechanisms of the TW. The dome is supposed to result primarily by folding and erosion with subordinate extension or in contrast, primarily by extension along the Brenner and Katschberg normal fault systems.

In order to constrain the tectonic regimes associated to Miocene exhumation in the brittle crust, we investigated brittle structures over the entire TW and we reconstructed paleostress fields by inversion. The paleostress orientations show a predominance of strike-slip regimes relatively to the normal and reverse ones. A clear zoning of the paleostress fields also exists. The overwhelming majority of transcurrent regimes is located within the central and south-western parts of the TW, while the eastern and western margins of the dome are dominated by extensional regimes. The direction of the minimal stress ($\sigma3$) is mostly ESE-WNW to ENE-WSW for the strike-slip regimes. Along the Brenner and Katschberg normal fault systems, normal regimes show $\sigma3$ oriented ESE-WNW and SE-NW, respectively.

Very few tensors indicate a compressive state of stress. Most of the inverse tensors are located in the core of the area whereas none of them are found at the western and eastern margins. The inverse tensors are characterised by a direction of $\sigma1$ ranging from NNW-SSE to NNE-SSW.

In view of the large-scale upright folds observed in the TW we expected a large number of tensors indicating N-S compression associated to the folding phase. However, in contrast to these expectations, few fault planes indicating compression have been found. These one probably represent the relics of brittle structures associated with the early formation of the TW by folding. Most of these structures were removed by erosion, leading to the exhumation of the folded ductile crust.

Strike-slip faulting in the central part of the TW and extension along the two bordering normal faults systems probably represent the youngest phase of deformation. It implies that rocks affected by extension and strike-slip faulting have been exhumed from deeper structural levels and have passed through the ductile-brittle transition later than the rocks affected by inverse brittle structures.

As the nearly northward motion of the Adriatic indenter during middle Miocene times was not anymore accomodateed by inverse brittle structures but by strike-slip faulting associated to normal faults, we proporse that a shift between compression mainly accomodated by vertical thickening to compression mainly accomodated by lateral extension must have taken place during the Miocene times. B oth structures accomodated orogen-parrallel extension.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

SRESS CONCENTRATION AND PERTURBATION IN NORTH WESTERN FRANCE

Nicole Béthoux[1] , Yves Mazabraud [1,2], and Bertrand Delouis[1]

[1] Université de Nice, Géosciences Azur, Villefranche sur Mer, France
[2] LaRGe, Université Antilles Guyane and IUFM de Guadeloupe, France

Hu and Angeler (2004) through 3D distinct element modeling explored a variety of simulations to characterize and interpret stress permutation in brittle tectonics. They demonstrated that variations in rheology are sufficient to induce stress perturbations. Their experiments indicate that the major causes of stress permutations are the heterogeneities of the brittle medium (intact rock massifs between heavily faulted deformation zones) and the anisotropy of the mechanical properties that result from fracturing and faulting. We apply their results to the case study of the North-western France. The Atlantic margin of France, known as an intraplate slow deforming region, is nevertheless subject to moderate earthquakes (Mazabraud et al., 2005). Some events of local magnitude larger than 5 sometimes occur such as the 2002/09/30 (ML = 5.7) Lorient event in Brittany and the different seismic crises located near the Oleron Island. The source study of these events shows an extensive deformation of this region, compatible with the extensive regional stress field, computed by several authors whereas the general western European stress field is known to correspond to a strike slip regime. We strongly argue that the switch of principal stress axes σ_1/σ_2 in a NW-SE vertical plane is linked to existence of crustal heterogeneities at the tip of weak heritated Hercynian shear zones, acting as channels were stress concentrates. 3D thermomechanical finite element modeling confirms the hypothesis of a strain localization that can be linked to the occurrence of moderate earthquakes in western France which is favored by preexisting faults and rheological contrasts. In particular, we show that the main event of our study area, the ML = 5.7 Lorient event, is located at the area where we model stress and strain accumulation near the intersection of two fault zones and just above a strong density contrast at the brittle-ductile transition zone. Study of Oleron crises underline the similarity of seismological behaviour between the south Armorican zone and the Charente coast, submitted to the same stress regime and sructuraly very comparable.

Hu J. C. and Angelier J., 2004, Stress perturbation: Three dimensional distinct element accounts for a common phenomenon in brittle tectonics. J. Geophys. Res., 109, B09403, doi: 10.1029/2003JB002616.

Mazabraud, Y., Béthoux, N., Deroussi, S., Characterisation of seismological pattern in an intraplate slow deforming region : central and western France. Tectonophysics, Vol. 409, 175-192, 2005

Perrot, J., Arroucau, P., Guilbert, J., Déverchère, J., Mazabraud, Y., Rolet, J., Mocquet, A., Mousseau, M. and Matias, L., Analysis of the Mw = 4.3 Lorient earthquake sequence: a multidisciplinary approch to the geodynamics of the Armorican Massif, Westernmost France. Geophys. J. Int., 162, 935-950, 2005.

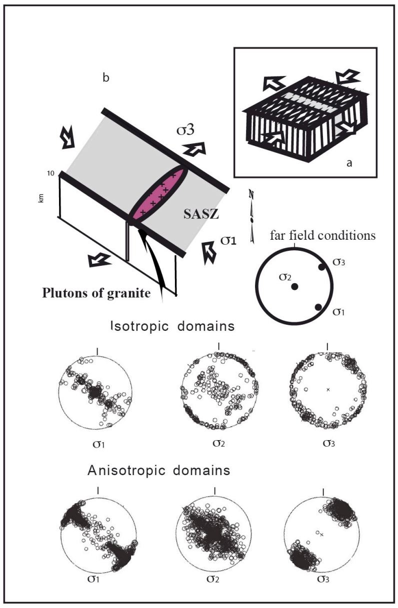


Figure 1

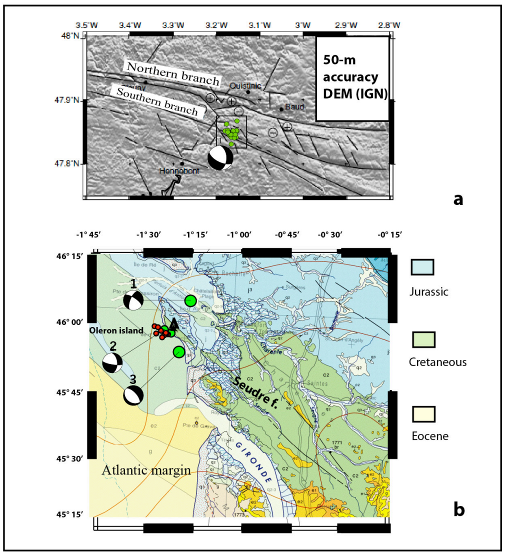


Figure 2

Fig1 a- Schematic block diagram and boundary condition of the 3D distinct element experiment modified after Hu and Angelier (2004). b- Application to the SASZ with plutons present. Model results of a strike-slip regime with s1 parallel to the faulting with s2 perpendicular to the anisotropy, modified after Hu and Angelier (2004)

Figure 2. *a- Distribution of the Lorient earthquake sequence, and faults observed in the field, modified from Perrot et al., 2005. The focal mechanism of the main event is reported. b – Epicenter distribution of 2005 Oleron sequence, superimposed on the geological map of the Charente region. The Oleron aftershocks swarm is indicated in red, the two events of magnitude higher than 4 in green. The focal solution of the 2005/04/18 event (2) is shown . The location of the 1972 event (1) as well as its focal solution is also schown as well as the 2010/09/28 event (3) . see Table 1 for references. The black triangle is the seismological station OLEF, located in the island, just close to the seismogenic zone.*

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

ROLE OF STRUCTURAL HETEROGENEITY ON FAULT ZONE PERMEABILITY: THE CASE OF DEEPLY BURIED TURBIDITIC ARENITES

(Annot Sandstone, SE France)

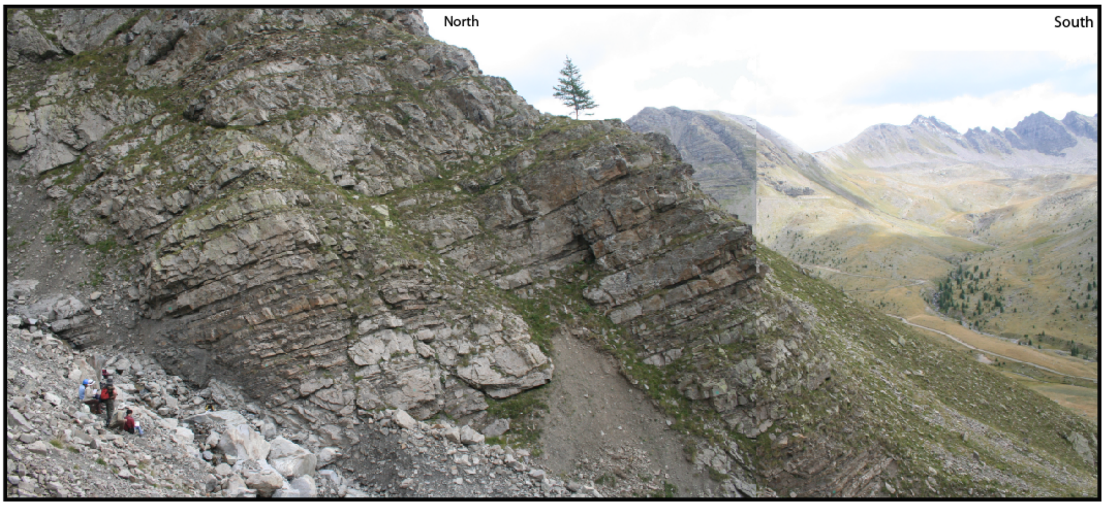
Thibault Cavailhes[1], Pierre Labaume[1], Jean-Pierre Sizun[2], Martine Buatier[2], Delphine Charpentier[2], Alain Chauvet[1], Roger Soliva[1], Anna Travé[3]

(1) Laboratoire Géosciences Montpellier, Université Montpellier 2 - CNRS, Montpellier, France
(2) Laboratoire Chrono-Environnement, Université de Franche-Comté - CNRS, Besançon, France
(3) Departament de Petrologia, Geoquimica i Prospecció Geològica, Universitat de Barcelona, Spain

Fault zones are major discontinuities in sedimentary basins. Understanding their role on fluid migrations is an essential issue to (i) characterize the mechanisms and kinematics of deformation and (ii) to determine the parameters which control the distribution of energetic or mineral resources. This work applies to faulting under a temperature range of 200-250°C, corresponding to that of deeply buried reservoirs as well as potentially sismogenic fault zones.

The studied faults are normal faults affecting the “Grès d’Annot” formation, a Priabonian–Rupelian siliclastic turbidite succession of the alpine foreland basin. The “Grès d’Annot” were tectonically buried under the Embrunais-Ubaye Nappes soon after their deposition and exhumed during the middle-late Miocene. The studied area is located in the eastern part of the basin, where vitrinite reflectance indicates maximal temperatures of 220-240°C, i.e a burial depth of 7-8 km assuming a mean geothermal gradient of 30°C/km. The faults affect alternating arkosic sandstone beds and pelite layers with offsets from centimeters to decameters (Fig. 1). The shear deformation affecting sandstone in the fault zone involves the combination of (i) pressure solution of quartz, (ii) intense fracturing sealed by quartz and calcite cements and (iii) the neoformation of (1) white micas derived from the alteration of feldspars and (2) chlorite. These mechanisms are responsible for a foliated fabric of the rocks in the fault core zone. Microthermometry of fluid inclusions and thermometric modelisation on neoformed chlorites suggest a fault temperature activity of approximately 220°C-240°C, consistent with the maximal burial depth of the studied formation under the nappes.

Combining a structural and microstructural study with permeability measurements on plugs oriented following the main axes of deformation (X, Y and Z) (Fig. 2), we show that the Y axis (mean axis of deformation, parallel to the veins and cleavage) is the preferential direction of potential fluid flow in the foliated arkosic sandstones characterizing the fault zone (10^{-2} mD for Y against 10^{-3} mD for X, Z and the protolith, measured at a confining pressure of 20 bars). We discuss also that the Y axis of deformation, which is parallel to the fault azimuth in the case of normal or reverse faults, is vertical in the case of strike slip faults. Hence, the preferential axis of fluid flow in the foliated fault rocks is, at all points of the fault zone, sub-perpendicular to the striation representative of the local movement, and this, at all scales.



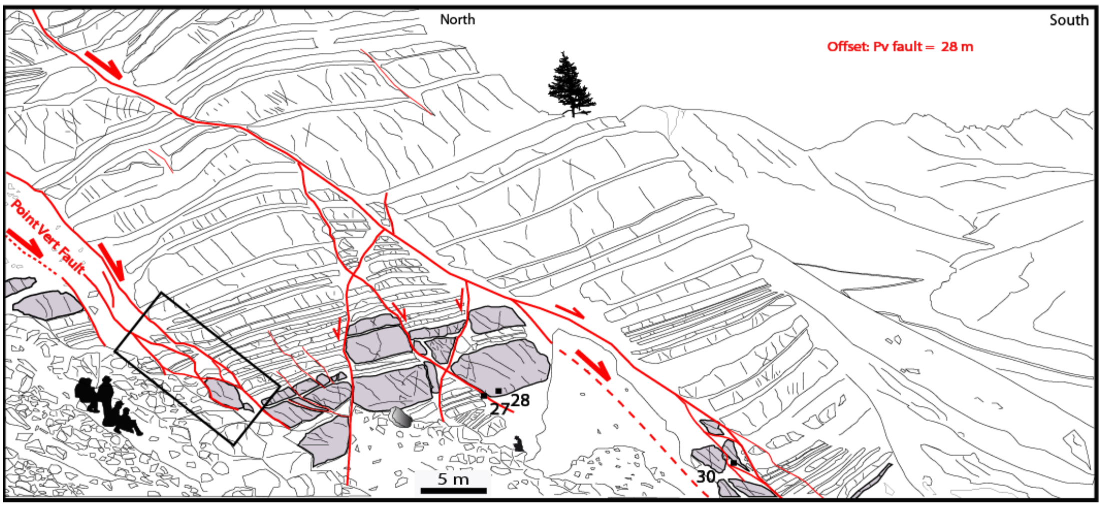


Figure 1. Studied fault zone of Point Vert and its structural interpretation.

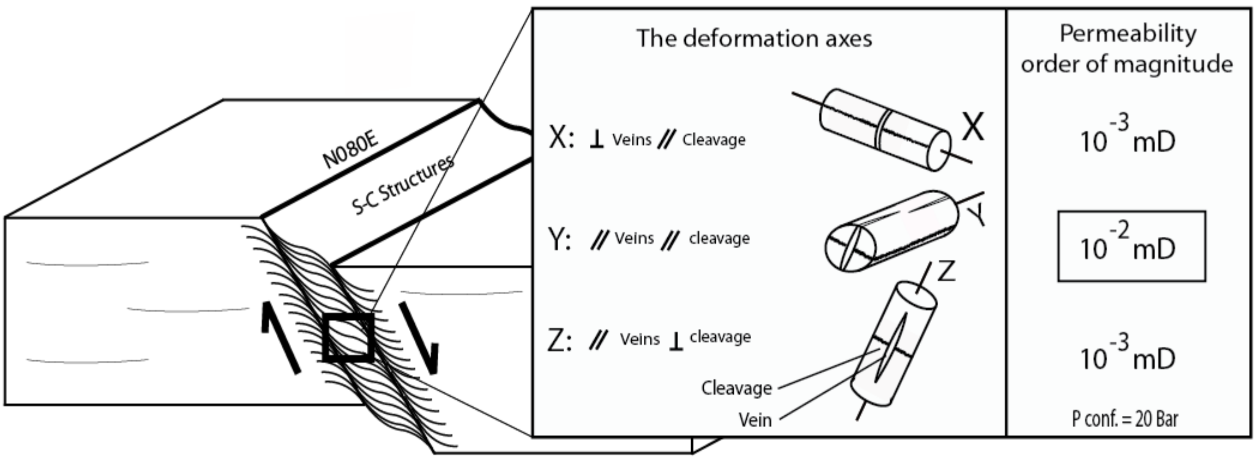


Figure 2. Orientations of plugs following the main deformation axes.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

REMARKS ON THE RELATIONSHIP BETWEEN THE PLUNGES OF THE P, B, AND T AXES OF EARTHQUAKE FOCAL MECHANISMS AND THE TECTONIC REGIME, THE RAKE OF THE SLIP VECTORS, AND THE DIP OF THE NODAL PLANES.

Bernard Célérier[1]

[1]Université de Montpellier 2 – CNRS, Geosciences Montpellier, Montpellier, France

The triangular representation of the P, B, and T axes introduced by Frohlich (1992; 2001) allows to easily compare the different ways tectonic regime is commonly inferred from earthquake focal mechanisms and to analyze the geometrical relationship between the plunges of P, B, and T axes on one hand, and the rake of slip and dip of nodal planes on the other hand.

When faulting is close to Andersonian conditions, P, B, and T axes provide a reasonable estimate of principal stress directions, and these conditions can be estimated from the location on the triangular diagram. When these conditions are not met, identifying P, B, and T axes with principal stress directions may result in angular errors up to 90° (MacKenzie, 1969; Célérier, 1988).

Alternatively, the plunges of the P, B, and T axes can be used to infer the faulting geometry: constant rake and dip correspond to trajectories of the vertical direction along great and small circles with respect to the P, B, and T axes frame (Célérier, 2010). This shows that dip-slip faulting is compatible with vertical P or T axes, but does not require it, and instead requires horizontal B axes. It also shows that strike-slip faulting does not require vertical B axes, but P and T axes with equal plunges. This also reveals that focal mechanisms where P, B, and T axes all have moderate plunge correspond to two very different types of nodal planes: a steeply dipping one with oblique slip and a moderately dipping one with strike-slip. Seismically active and moderately dipping strike-slip faults are to be found among these events.

References

Célérier, B., 1988, How much does slip on reactivated fault plane constrain the stress tensor ? *Tectonics*, **7**, 1257–1278, 1988.

Célérier, B., 2010, Remarks on the relationship between the tectonic regime, the rake of the slip vectors, the dip of the nodal planes, and the plunges of the P, B, and T axes of earthquake focal mechanisms, *Tectonophysics*, **482**, 42-49.

Frohlich, C., 1992, Triangle diagrams: ternary graphs to display similarity and diversity of earthquake focal mechanisms, *Physics of the Earth and Planetary Interiors*, **75**, 193–198.

Frohlich, C., 2001, Display and quantitative assessment of distributions of earthquake focal mechanisms. *Geophysical Journal International*, **144**, 300–308.

McKenzie, D. P., 1969, The relation between fault plane solutions for earthquakes and the directions of the principal stresses, *Bull. Seismol. Soc. Am.*, **59**, 591–601.

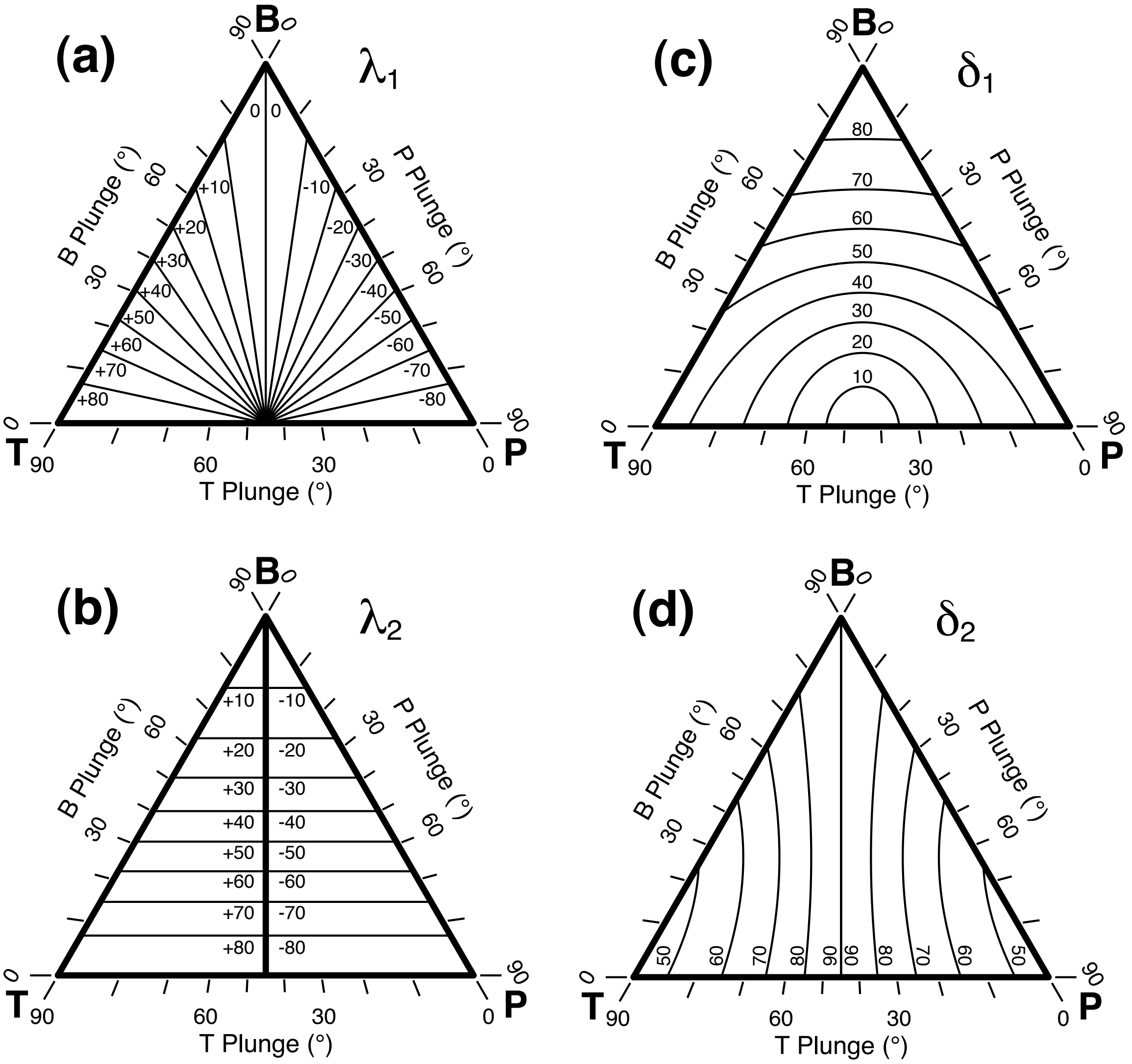


Figure 1. (a) First nodal plane rake level curves defined as λ1. (b) Second nodal plane rake level curves defined as λ2. The curves are shown for rake within [−90°, 90°] by increment of 10°. Levels curves for supplementary rake are identical to each other. If rake is directly read on one curve for one nodal plane, the rake for the other nodal plane is the supplement of the rake read on the other curve. (c) First nodal plane dip level curves defined as δ1. (d) Second nodal plane dip curves defined as δ2.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

FAULT SEGMENTATION AND STRUCTURAL EVOLUTION OF THE FRONTAL LONGMEN SAN FAULT ZONE

Chung-Pai Chang [1, 2*], Xi-Wei Xu [3], Ren-Mao Yuan [3], Kang Li [3], Xin-Zhe Sun [3], Wen-Shan Chen [4]

[1] Center for Space and Remote Sensing Research, National Central University, Jhongli, 32001 Taoyuan

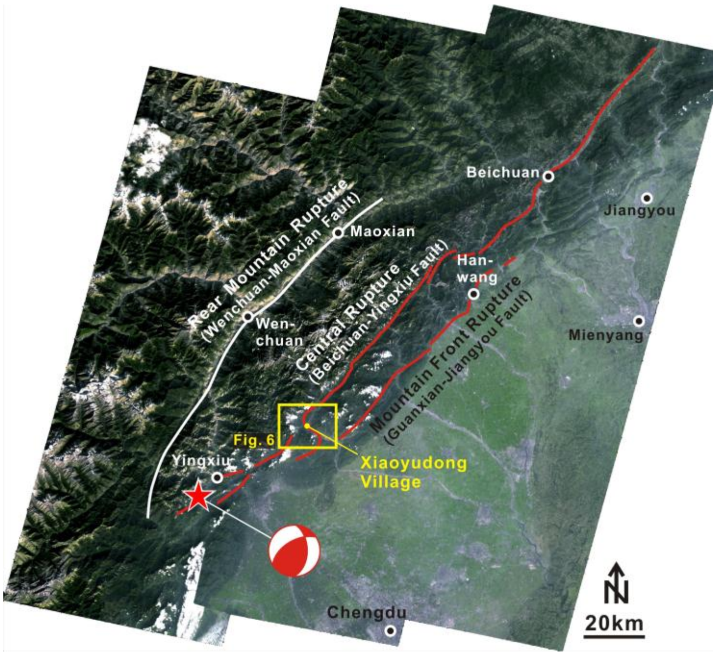
[2] Institute of Geophysics, National Central University, Jhongli, 32001 Taoyuan

[3] Institute of Geology, China Earthquake Administrative, 10029 Beijing

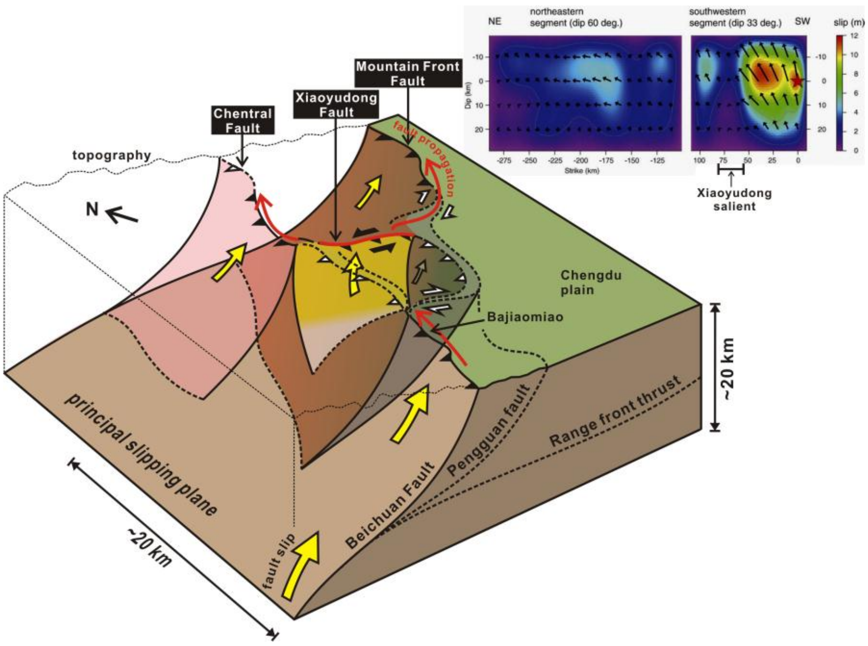
[4] Department of Geosciences, National Taiwan University, 10617 Taipei

Keywords: Longmen San fault zone, Wenchuan earthquake, structural evolution, multi-segment rupturing

Field investigations show that the Wenchuan earthquake on the 12th of May 2008 ruptured two NW-dipping imbricate reverse faults along the Longmen Shan fault zone at the eastern margin of the Tibetan Plateau. The length of the Beichuan-Yingxiu Fault reaches nearly 240 km. Southeast of this fault, a smaller displacement occurred along the Guanxian-Jiangyou Fault, which has a length of about 70 km. A 7 km long NW-striking left-lateral reverse fault, the Xiaoyudong Fault, was clearly observed between these two main surface ruptures. This co-seismic surface rupture pattern, involving multiple structures, is one of the most complicated patterns of recent great earthquakes. The surface rupture length is the longest among the co-seismic surface rupture zones for reverse faulting events ever reported. Our detail field investigations reveal that the surface rupture of the Wenchuan earthquake cascaded through several pre-existing fault segments. The displacement amount, the rupture pattern and the stress orientation calculated from the fault slickenside striations between the different segments are all different. Some secondary faults can also be observed between the segments. These faults are partially active and control the development of river terraces and the shape of streams. We suggest that the multi-segment rupturing model is a better approximation than a single-segment model for estimating the maximum magnitude of the Longmen Shan fault zone.



SPOT-5 image acquired after the earthquake. Previous field investigations show that the Wenchuan earthquake ruptured two imbricate reverse faults along the Longmen Shan fault zone as shown by the red lines. The red star shows the epicentre of main shock of the Wenchuan earthquake. The focal mechanism solution is from United States Geological Survey.



The block diagram shows the possible geometry of the Xiayudong salient. Black lines on the surface are observed faults, and dotted lines are deformation zones (without continuous surface rupture). The underground structures are principally after Burchfiel et al., 1995. Yellow arrows on the fault planes roughly show the relative slip amount. Red arrows on the surface indicate the fault propagation direction. The upper right panel is the slip distribution model inferred from the waveform inversion (Nakamura et al., 2010).

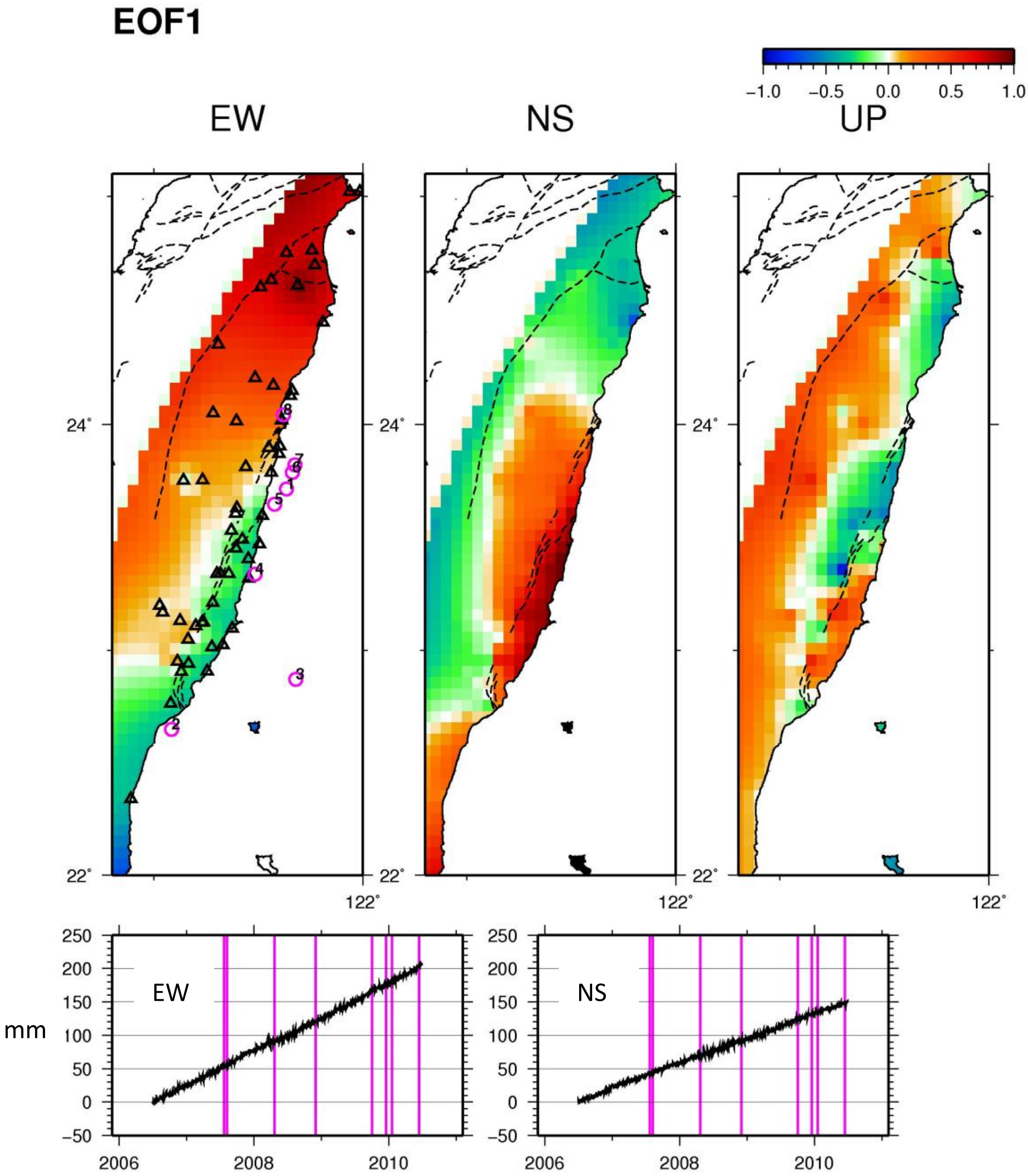
Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

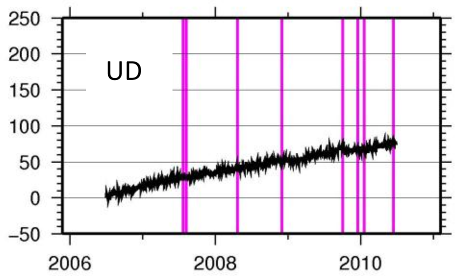
CRUSTAL DEFORMATION IN TAIWAN AND ITS VICINITY FROM CGPS DATA

Emmy T. Y. Chang[1], Benjamin F. Chao[2], and Lin-Guo Yuan[2,3]

[1]Institute of Oceanography, National Taiwan University, Taiwan
[2]Institute of Earth Sciences, Academia Sinica, Taiwan
[3]Faculty of Geosciences and Environmental Engineering, Southwest Jiaotong University, China

The island of Taiwan, along with the vicinity region including the Ryukyu subduction zone, represents a fastest convergence in the world. It occurs as the Philippine Sea plate obliquely subducting beneath Eurasian plate. In the last decade or so, continuous GPS (CGPS) network in Taiwan has become available for investigation of the tectonic motion and crustal deformation in the region. We performed state-of-the-art Precise Point Positioning (PPP) processing of these CGPS data for different time spans at different time resolutions. We determine the 3-D, long-term tectonic motion of the island in different tectonic settings, and in particular the vertical motion in relation to the orogeny process, which is also compared with the ground leveling data. The method of Empirical Orthogonal Functions (EOFs) is employed on the CGPS position time series to obtain and examine the synoptic as well as detailed spatio-temporal behavior within the seismic cycle within the convergent process. The principal components, or "modes", of the crustal deformation extracted by the EOFs analysis can be further applied to calculate the horizontal strain field at the surface. This strain field, calculated for co-seismic as well as inter-seismic deformation, exhibits interesting spatial pattern that provides further insight toward a better understanding of the dynamic and complex seismotectonics of the region. We also study the vertical-motion rates along with the seismic activities especially in the Longitudinal Valley (LV) in eastern Taiwan, which the suture zone between the Philippine Sea plate and the Eurasian plate. Our result reveals a segmented pattern for the interseismic deformation. Judging from the different behavior between the co-seismic and aseismic vertical motions marked by the major earthquakes during the studied period, we postulate a temporal saw-tooth scenario for the deformation in phases in the eastern Taiwan.





Example of the spatial and temporal distribution of the EOF analysis with GPS position time series. Here is the first EOF modes of the ground motion in 3 components for the east Taiwan. The color plots present the intensity of the ground motion corresponding to the time series showing below. The dashed curvy lines in the spatial patterns indicate the active faults. The pink circles and the black open triangles illustrate respectively the epicenter of 8 large events and the GPS stations used for the EOF analysis. The pink lines in the below time series plots indicate the origin time of 8 earthquakes.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

APPLICATION OF IN SITU-PRODUCED COSMOGENIC NUCLIDES TO DECIPHER ACTIVITY OF THE DEFORMATION FRONT IN WESTERN TAIWAN

Rou-Fei Chen[1,2], Florence Derrieux[3], Lionel Siame[3], Kuo-Jen Chang[4], Jian-Cheng Lee[2], Régis Braucher[3], Der-Chun Lee[2], Didier Bourlès[3] and Yu-Chang Chan[2]

[1] Univ. Chinese Culture, Dept. Geology, 11114, Taipei, Taiwan.
[2] Academia Sinica, Inst. Earth Sciences, 11529, Taipei, Taiwan.
[3] Univ. Aix Marseille, UMR 6635, F-13545, Aix-en-Provence, France.
[4] Univ. Taipei Technology, Dept. Civil Engineering, 10608, Taipei,Taiwan.

The western foothills of Taiwan represent a major part of the passive Eurasian margin and comprise a typical thin-skinned fold-and-thrust belt. The HsiaoMei anticline is located between a series of mountain-front-bounding laterized terraces and the Chiu-Chiung-Keng fault. It is an active fault-propagation fold associated with a small amount of reverse slip along upper portions on the original normal fault, the blind thrust HsiaMei fault. The first task of this study is to assess whether the growth of the Western Foothill Belt can be linked to the shape of geometry and the kinematics development of the fold-and-thrust belt. Hence, methods suitable for correlate the river terraces in subtropical climatic condition of Taiwan are investigate in this study, and is dedicated further to identify the relationship between river terraces formation and tectonics activities. But many geochonological dating techniques are not applicable to age range between 50K and 300K years old. To achieve these scientific goals, the analysis should combine both the quantitative geomorphology based on high resolution DEM and the statistical curve fitting from the cosmogenic nuclides concentration (^{10}Be) measured in alluvial terraces profile.

In this study, we use two cosmogenic dating methods for two different fluvial depositions. Our results indicate that two potentially active structures, the HsiaoMei anticline is characterized growth fold and associated with the blind thrusting (HsiaoMei fault) in western Taiwan. In Chiayi area, the Santieh River associated with the growth of the Hsiaomei Anticline by the incision rate of 0.2 cm/yr, integrated over the last ~40 kyr. The folding inception associated to the blind-thrust HsiaoMei Fault, and the shortening rate of the growth anticline is on the order of ~0.5 cm/yr. The chronological framework of entrenchment and abandonment of the Pachang alluvial terraces spans the last 14 kyr, we using Chukou boulders exposure age to calculate the age of different terrace gradients. The results allowed of the new reassessment about the occurrence of the river terraces deposits, thus, cosmogenic profiles dating can provide a useful tool to distinguish depositional hiatus in Chiayi area.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

TECTONIC AGGRESSION AND RETREAT MODEL IN CONTINENTAL MARGIN

Pom-yong Choi[1]

[1] Korea Institute of Geoscience and Mineral Resources, 124, Gwahangno, Yuseong-gu, Daejeon, 305-350, Korea.

The Neogene tectonics of the Korean Peninsula displays a gradual change in regional compression direction from WNW-ESE in the Late Miocene through E-W in the Pliocene to ENE-WSW in the Quaternary. The movement of a plate produces a certain amount of tectonic stress. The range of tectonic influence corresponds to the ‘tectonic domain’; the Present ENE-WSW compression exerted on the Korean Peninsula wholly belongs to that of the Himalayan tectonic domain (HTD). Likewise, the Philippine Sea tectonic domain (PSTD) corresponds to the area where NW-SE compression prevails in relation to the Philippine Sea Plate. Tectonic domain may vary from time to time, depending on the relative tectonic force compared with those of neighboring plates. Assuming the tectonic stresses of the HTD and PSTD, the Late Miocene and Pliocene principal stresses are decomposable into the stress components of these two tectonic domains; Neogene tectonic stress change can be illustrated in terms of the diminishing tectonic influence (or ‘tectonic retreat’) of the Philippine Sea tectonic domain.

Fault tectonic analysis of the Quaternary formations in the Pohang-Ulsan area, SE Korea displays three faulting events such as the ENE-WSW, NW-SE to WNW-ESE and N-S compressions nearly coexisting during the Quaternary. This tectonic setting can also be explained in terms of tectonic ‘aggression and retreat’ model between the related tectonic domains. As seen in the Present tectonic setting, the aggression of the Himalayan tectonic domain is inferred in the Korean Peninsula which is responsible for the Present ENE-WSW compression in the Korean Peninsula, while that of the Philippine Sea tectonic domain produces the NW-SE to WNW-ESE compression in the Pohang-Ulsan area.

As to the current tectonics of the Inner Zone of SW Japan, E-W compression prevails, and not a few active faults and Quaternary formations develop in this area. The NW-SE trending Yamasaki, Tonoda and Mitoke faults displaced the pre-Quaternary formations in a dextral sense presumably in N-S or NNW-SSE compression, but the drainages in a sinistral sense. Similarly, the NW-SE trending Atera and Neodani faults also show sinistral motions.

In contrast, the NE-SW trending Atotsugawa, Enako and Hanaore faults show dextral motions at present. At the same time, N-S trending faults in the Inner Zone show vertical (reverse) movements. It is certain that the Inner Zone of SW Japan now lies in E-W compressive stress field as seen in focal mechanism data. In the Outer Zone including the Kii Peninsula, a tectonic 'shadow zone' is assumed where few active faults and Quaternary formations develop.

Fault tectonic analysis of the Kii Peninsula near the Nankai subduction zone reveals six faulting events in sequence: (1) E-W extension; (2) E-W compression and N-S extension; (3) NNW-SSE compression and ENE-WSW extension; (4) NE-SW compression and NW-SE extension; (5) WNW-ESE compression and (6) NNE-SSW extension. N-S to NNW-SSE trending dike swarm of Middle Miocene age in the Kii Peninsula is thought to be related to Event 3, implying that Event 3 was active at least during the Middle Miocene. Because Event 6 is recognized solely at a site, the overall latest faulting event seems to be Event 5. Assuming that the compression results from the motion of the crust or plate, the compression direction of Event 5 is in good accordance with the present-day west-northwestward crustal velocity vectors of the Kii Peninsula. The stress trajectory map of SE Korea and SW Japan reveals that the current compression directions of the Kii Peninsula correspond to the combinatory stress fields of the Himalayan and Philippine Sea tectonic domains.

In the area where several plates are situated, the tectonic sequence would be decomposable into stress fields related to the participating tectonic domains, and should be interpreted in terms of interation of the tectonic domains.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

ESTIMATE OF BURIAL DEPTH CHANGE DURING SEDIMENTATION OF NW GYEONGSANG BASIN (CRETACEOUS), KOREA

Pom-yong Choi[1]

[1] Korea Institute of Geoscience and Mineral Resources, 124, Gwahangno, Yuseong-gu, Daejeon 305-350, Korea.

In the elastic model, the natural stress field consists of horizontal compressive and extensional stress increments and vertical load. In this model, stress difference ratio $\Phi= (\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$ shows a linear relationship with respect to the vertical load. Linear relations are found between the vertical load and the reciprocal of Φ in extensional tectonic regime as well as between the former and Φ in compressive tectonic regime. The slopes and intercepts of these linear relations permit us to determine the horizontal stress increments and depths of average paleo-surfaces. In SE Korea, more than fourteen faulting events are recognized through fault tectonic analysis using fault-slip data and tension gashes. The earliest tectonic event (T_1 Event) has been active at least during the Barremian–Cenomanian period, and consist of compressive and extensional faulting events showing mostly E-W compression or N-S extension. These two faulting events coexisted, and so the relative chronology shows the two deformed each other. On the basis of fault tectonic analysis of sites in NW Gyeongsang Basin, plot of stress difference ratios against the vertical load displays several clusters showing linear relations: two clusters in the extensional events and more than two in the compressive events. Each cluster corresponds to one of tectonic episodes during the T_1 Event. Assuming that the horizontal compressive stress increment is null in the extensional tectonics, the horizontal extensional stress increments are determined from the slopes of two linear clusters as –2.5 ~ –4.0 MPa. In compressive events, the horizontal stress increments are determined to be 70~114 MPa by applying the upper horizontal extensional stress increments. Determined depths of average paleo-surfaces and those of syndepostional structures show that more than five episodes have occurred during the T_1 Event. It is concluded that the alternating compressive and extensional episodes correspond to the coexitence of these in relative chronology.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

FAULT AND JOINT PATTERNS ACROSS A MOUNTAIN BELT IN NORTHERN TAIWAN

Hao-Tsu Chu [1-6], Jyr-Ching Hu[2-6], Françoise Bergerat[3-6], Jian-Cheng Lee[4-6], Shen-Hsiung Liang[1-6], Jacques Angelier[5-6], Chia-Yu Lu[2-6]

[1] Central Geological Survey, MOEA, Taipei, Taiwan, ROC

[2] Department of Geosciences, National Taiwan University, Taiwan, ROC

[3] ISTeP, UMR 7193 CNRS-UPMC, Paris, France

[4] Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan, ROC

[5] GEOAZUR, UMR 6526 CNRS-UNS-UPMC-IRD, Villefranche-sur-Mer, France

[6] International Laboratory « ADEPT », CNRS -NSC France-Taiwan

The main purpose of this study is to apply fracture analysis based on field measurements of faults, joints and related fractures in the exterior and interior fold-and-thrust mountain belt in northern Taiwan. The principal stress axes $\sigma 1$, $\sigma 2$, $\sigma 3$, were calculated from the measured fault populations at each site. The indicator for the compressive direction of the joint system is the acute bisector between conjugate joints.

The geometrical orientations of conjugate shear joints, conjugate hybrid joints, spaced cleavage, and tension joints suggest that compressive stress was trending mainly SE-NW or SSE-NNW. The maximum compressive axis $\sigma 1$ independently derived from the measured fault planes in the studied sites has the same orientations ranging from azimuths 105° to 165°.

The spreading of the compressive stress axis is probably due to compressive events in different directions. The first compressive event was orientated N150° E and the last N120° E. These directions match the movements of the Philippine Sea plate by former studies.

The coincidence of the acute bisector of the conjugate joints with the maximum compressive stress axis at several sites strongly suggests the existence of a common compressive regime between the joints and faults. Field studies showed that there is an obvious consistency in the formation of compression in fault and joint patterns across the exterior and interior fold-and-thrust mountain belt in northern Taiwan.

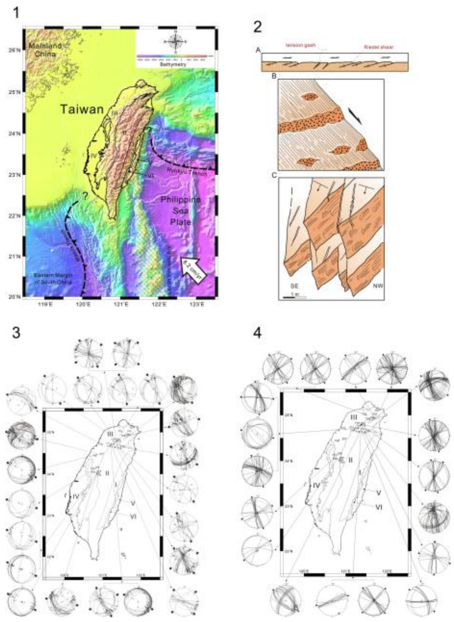


Figure – 1. Taiwan is located at the convergent boundary between the Philippine Sea Plate and the Eurasia Plate. It can be divided into 6 units in terms of tectonics, I: Eastern flank of the Central Range subunit (i.e., the Tananao metamorphic complex); II: Western flank of the Central Range subunit (i.e., the Tertiary slate and argillite); III: Western foothill unit; IV: Coastal plain unit, V. Coastal Range (i.e., the Luzon arc) and VI: Longitudinal Valley (after Ho, 1986). 2. (A) Riedel shears (movement indicated by small arrows) and tension gashes. (B)Distribution of rough facets (dotted) and polished facets (hachured) on a fault surface. (C) Conjugate strike-slip faults with slickensides and the associated en echelon quartz veins. 3. Analysis of fault-slip data sets. Faults shown as thin planes; Bedding planes shown as thin dashed lines and poles of bedding planes shown as open dots; slickenside lineations shown as small dots on fault planes with small, outward directed arrows (normal slip), inward directed arrows (reverse slip) or double arrows (dextral or sinistral slip). Computed paleo-stress axes $\sigma 1$, $\sigma 2$ and$\sigma 3$ shown as 5-, 4- and 3- pointed stars respectively. Large black arrows indicate computed directions of extension and compression. 4. Analysis of other fracture data sets, especially joints. Joints shown as thin planes; Bedding planes shown as thin dashed lines and poles of bedding planes shown as open dots; Computed paleo-stress axes $\sigma 1$ shown as solid triangles.

Reference

1. Angelier, J., Barrier, E. and Chu, H.T., 1986. Plate collision and paleostress trajectories in a Fold-Thrust Belt: the Foothills of Taiwan. Tectonophysics, 125, 161-178.
2. Chu, H.T., 1990. Néotectonique cassante et collision Plio-Quaternare à Taiwan. Thèse doctorat de l'Université Paris VI, 292p.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

CONFÉRENCE INVITÉE – INVITED CONFERENCE

AN ENDOGENOUS ORIGIN FOR THE PRESENT DAY STRESS FIELD IN THE PARIS BASIN

François Henri Cornet[1] and Renaud Toussaint[1]

[1] Institut de Physique du Globe de Strasbourg, francois.cornet@unistra.fr

Jacques Angelier has always been a strong promoter for applying principles of mechanics to structural geology. In 2005 a special session on regional stress field characterization was organized at the annual meeting of the European Geophysical Union during which Jacques gave an invited talk on this topic. The object of the present paper is to follow up on this discussion about stress decoupling in sedimentary basins, as a tribute to Jacques's contribution to understanding stress fields in geological materials at various scales.

It is often considered that, at a multi kilometre scale, the stress field in the upper crust varies linearly with depth independently of rock type (e.g. Brace and Koelstedt, JGR, 1980; Zoback, 2007). This linear variation is taken as a consequence of the hypothesis that the upper crust is always close to failure and that failure is controlled by slip on optimally oriented pre-existing faults. Yet, at the scale of tens of meters, it is well known in the oil industry that within sedimentary formations the vertical gradient of the minimum horizontal principal stress does not vary linearly with depth. This is well demonstrated by the limited vertical extension of hydraulic fractures that propagate horizontally over distances larger than a few hundred meters in stratified formations (e.g. Economides & Nolte, 2003). Because generally the minimum horizontal principal stress magnitude is smaller in stiff rocks like limestone or sandstone than it is in the clay rich materials that are underlying and overlying the stiff formations, hydraulic fractures remain confined within the stiffest formations. This has been often confirmed through microsismic monitoring of large (100 m scale) hydraulic fracture propagation (e.g. Rutledge and Philips, 2003; Sileny et al., JGR, 2009). In this presentation we discuss detailed observations on vertical stress variations within the Paris Basin sedimentary formations. This helps outlining the influence of the rheological characteristics of geomaterials on vertical stress profiles. We discuss then the origin of the stress field in this region that supports no detectable active tectonic deformation.

For the last fifteen years, ANDRA, the French radioactive waste management agency, has been investigating the possibility of developing a long term repository in the eastern Paris Basin, near the small village of Bure (Haute Marne). There, the targeted 150 m thick Callovo-Oxfordian (COX) clay rich layer (argillite) is interbedded between the 224 m thick Dogger limestone (below) and the 212 m thick Oxfordian limestone (above), all of which are sub-horizontal (dip smaller than 3 degrees). Design of a potential repository requires an accurate determination of the complete natural stress field within the argilite formation and its surrounding.

The volume that has been investigated extends over an area about 100 km^2, within a depth range that varies from 300 m to 750 m. A first set of measurements was conducted in the immediate vicinity of the Underground Research Laboratory (URL) that has been developed for conducting the required in situ testing. This stress determination relied on hydraulic tests in boreholes including both classical Hydraulic Fractures (HF) and Hydraulic Tests on Pre-existing Fractures (HTPF). Vertical, inclined and horizontal boreholes have been taken to advantage so that axial and en echelon fractures have been analyzed for a precise evaluation of the orientations and magnitudes of all three principal stress components.

Also, because the argilite compressive strength as measured in the laboratory depends on whether the samples have been collected in cores obtained with oil based mud (stronger) or with water based mud (weaker), the appearance or non appearance of borehole breakouts has been used to define upper bounds and lower bounds to the maximum horizontal principal stress magnitude (see Wileveau et al. (Phys & Chem. of the Earth, 2007) or Cornet (2010) for a detailed discussion on these methods and results). Results obtained at the URL site are summarized in figure 1.

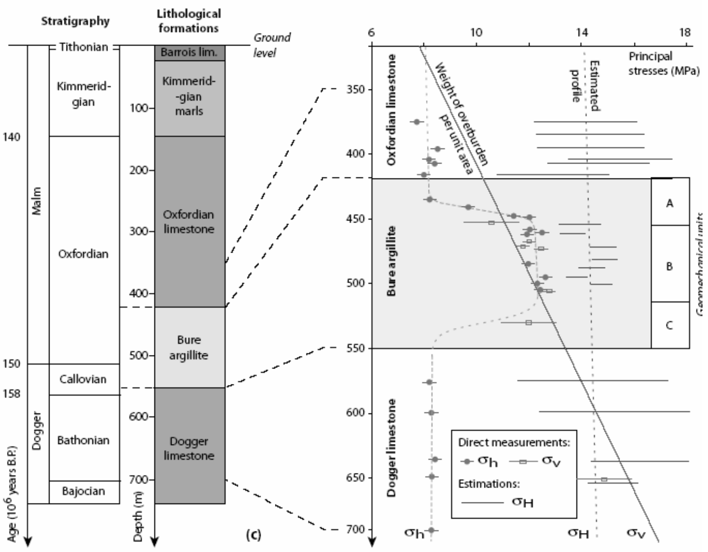


Figure 1. Results from the complete stress determination at the Under Ground Laboratory (URL), in the Eastern Paris Basin (Wileveau et al., Phys. & Chem. of the Earth, 2007).

Results have been confirmed by additional measurements in vertical boreholes located some 15 km away from the Underground Laboratory in the North East and in the North West directions (Cornet and Roeckel, Tectonophys., 2011).

These results raise two questions:

- What causes the deviatoric stress observed in the Oxfordian limestone given the deviatoric component in the underlying Callovo-Oxfordian argillite is much smaller and given there is no presently active tectonic deformation process in the Paris Basin ?
- How do we explain the small but existing deviatoric stress in the Callovo-Oxfordian argillite, given the rheological properties measured in the laboratory for this material suggest they should vanish within about 1000 years?

The absence of active tectonic is demonstrated both by the absence of microseismic activity and by the repeated geodetic GPS measurements that show no detectable horizontal displacements in the Paris Basin (Noquet & Calais, GJI, 2004).

Interestingly, various observations have shown the ubiquitous N 150°E orientation of the fracture field at various scales in the Paris Basin. This direction is parallel to the measured maximum horizontal principal stress direction. It has been verified that a small fluid flow along this fracture system would dissolve material in the direction perpendicular to the fracture field, resulting in a decrease in the minimum horizontal principal stress. This occurs mostly in the limestone formations, which, as a consequence, load in turn the argillite formation and induce therefore a small deviatoric stress in this formation. This process is consistent with the pore pressure profile observed within the argillite, a profile that remained unexplained before the present proposition.

We conclude that the stress field in the Paris Basin sedimentary formations is not controlled by friction along optimally oriented pre-existing faults but by the rheology of the materials and their deformation associated with large scale fluid circulations.

RECONSTRUCTION OF THE KINEMATIC EVOLUTION IN THE QUEFFLEUTH CATACLASTIC ZONE OF THE NORTH-ARMORICAN SHEAR ZONE, BRITTANY, FRANCE

Tine Derez[1], Sara Vandycke[2], Tom Haerinck[1], Isaac Berwouts[1] and Manuel Sintubin[1]

[1] Geodynamics & Geofluids Research Group, Department of Earth & Environmental Sciences, Katholieke Universiteit Leuven, Celestijnenlaan 200E, 3001 Leuven, Belgium
[2] Géologie Fondamentale et Appliquée, University of Mons, Faculté Polytechnique, 9 rue de Houdain, 7000 Mons, Belgium

The *North-Armorican shear zone* (NASZ) is described as a through-going, east-west oriented, dextral transcurrent shear zone, that crosscuts the Palaeozoic Armorican massif in the north. As the exposure degree along the NASZ is very low, the Queffleuth valley offers a unique opportunity to study the kinematics of the shear zone on a well-exposed road cut, oriented perpendicular to the NASZ. Further, the faults of the *Queffleuth cataclastic zone* (QCZ) are used to test the validity of a paleostress analysis in the brittle-ductile regime. The QCZ is 60 meters wide and developed from a granitic protolith (Commana granite). In the QCZ, four morphological classes of faults are observed. Class A can be linked directly with cataclasis, as the matrix-to-clast ratio increases and the clast size decreases towards the faults. Classes B, C and D crosscut the cataclasitic rocks. The crosscutting nature indicates that fault activity must have taken place at the end of, or after, the cataclastic deformation. In thin sections of the cataclasites, both dextral and sinistral shear sense indicators are observed. A detailed paleostress analysis reveals five distinct stress states (figure). Each of the morphological classes cannot be attributed to a single stress state, so that no correlation between the fabric of the faults and the stress states is apparent. While the magnitude of the stresses is highly variable, the quality parameters for the orientation give satisfying results. Paleostress analysis on brittle-ductile shear zones thus appears suitable to determine the orientation of the principal stress axes. Stress states 3 and 4 indicate dextral kinematics and are thus conform with the main dextral shear activity of the NASZ. Stress states 1 and 2 are thought to be precursors of the main activity. Possibly, the deformation during these stages took place in the ductile regime, during which the trend of the maximum horizontal stress

oscillated between ESE and SSE. Additionally, a sinistral activity is inferred from stress state 5. The latter can be seen as a relaxation event predating (scenario 1) or postdating (scenario 2) the main dextral shearing. A cyclic evolution between dextral and sinistral kinematics can though not be excluded (scenario 3). Based on our study, two characteristics of the NASZ, commonly described in literature, need reassessment. Firstly, our study shows that the rocks in the QCZ are protocataclasites to cataclasites, in contrast to the ultramylonites indicated on the geological map (Cabanis et al., 1981). Secondly, a sinistral activity is inferred for the NASZ, which has never been demonstrated in literature to date.

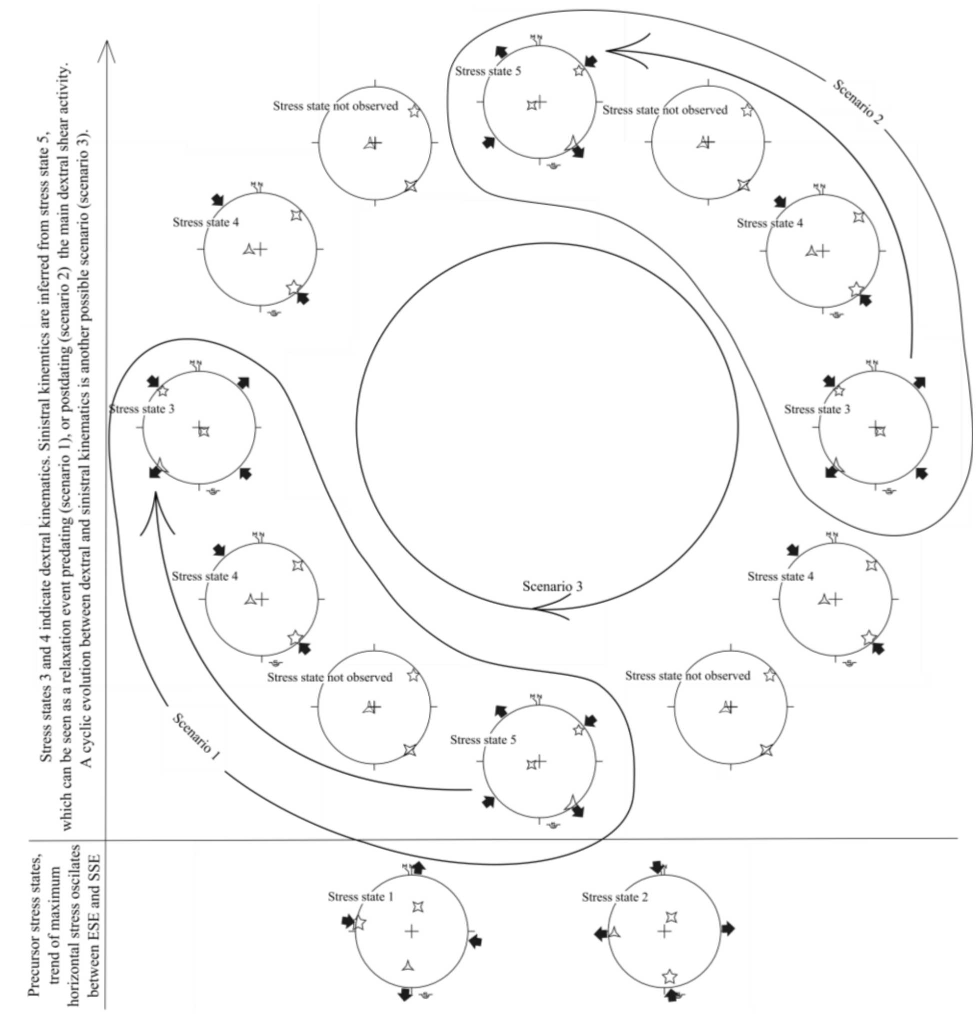


Figure : Kinematic evolution in the QCZ of the NASZ. The diagrams contain the computed principal stress axes σ_1, σ_2 and σ_3, shown as 5-, 4- and 3-branched stars respectively. The large black arrows indicate the directions of maximum and minimum horizontal stress. These plots are the results of paleostress analysis with the software TENSOR designed by Prof. Dr. J. Angelier.

Cabanis, B., Chantraine, J., Jebrak, M., Dadet, P., Herrouin, Y., Huber, P., Flageollet, J.-C., Chauris, L., Garreau, J., Beaujour, A., Duhamel, M., 1981, Carte géologique de la France a 1/50 000, feuille Morlaix (240), Bureau de Recherches Géologiques et Minières, Orléans.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

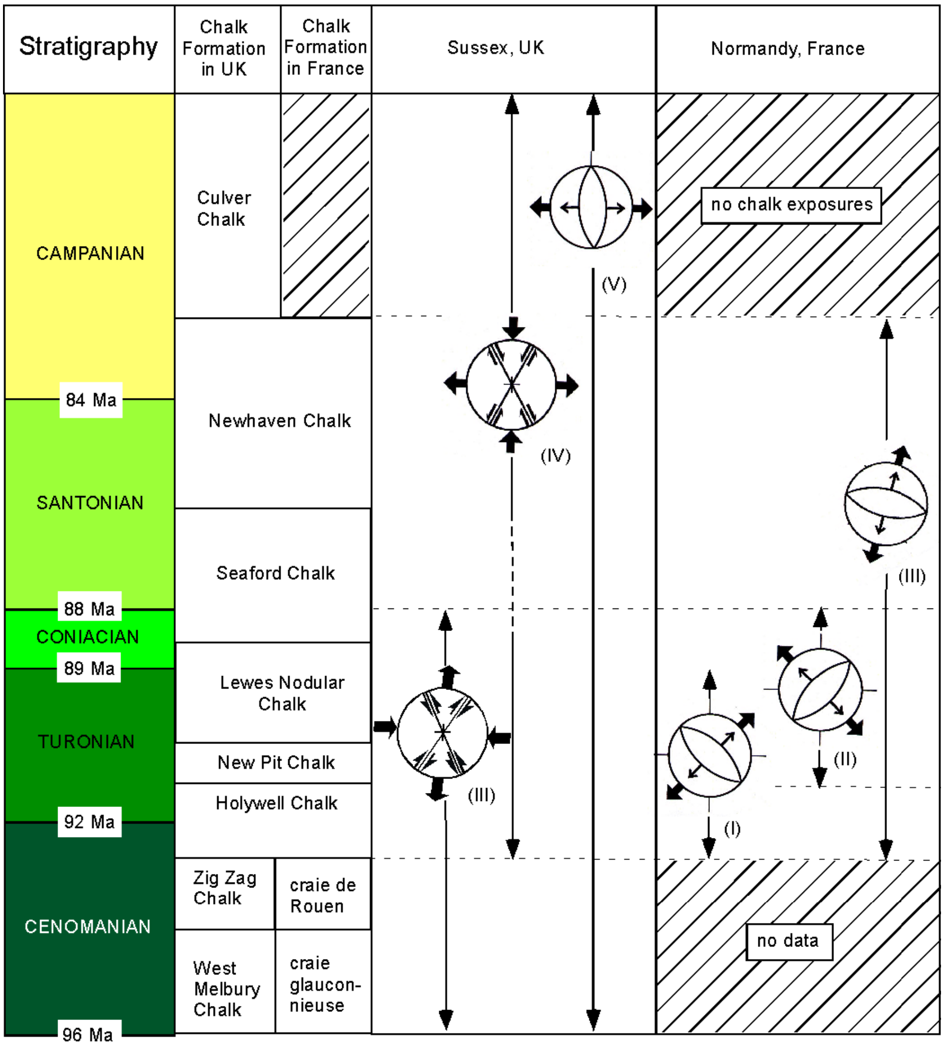
THE USE OF PALEOSTRESS ANALYSIS TO DETERMINE HOW IS RECORDED PLATE TECTONICS IN CHALK DEPOSITS ALONG THE EASTERN ENGLISH CHANNEL IN NORMANDY (FRANCE) AND SUSSEX (UK)

Anne Duperret[1], Sara Vandycke[2], Rory N. Mortimore[3] et Albert Genter[4]

[1] FRE 3102 LOMC CNRS-Université du Havre, 76058 Le Havre, France
[2] FNRS-Université de Mons, Faculté Polytechnique, 7000 Mons, Belgique
[3] Chalk Rock Ltd, 32 Prince Edwards road, Lewes, Sussex BN71BE, United Kingdom
[4] BRGM, BP36009, 45060 Orléans cedex et GEIE Exploitation Minière de la chaleur, route de Soultz, BP 40038, 67250 Kutzenhausen, France

Intra-plate stresses occurred in the Anglo-Paris Basin and English Channel during Upper Cretaceous and Cenozoic times as a consequence of the convergence between Eurasia and Africa and the opening of the North Atlantic area. This geodynamic re-organisation is recorded each part of the English Channel, with the emergence of regional structures like the Weald-Artois anticline and the reactivation of large-scale strike-slip faults. We analyse the Anglo-Paris basin Chalk fracture system, on each part of the eastern English Channel, using a set of 1600 meso-scale fractures data collected on coastal chalk cliffs in Normandy (NW France) and Sussex (UK). Meso-scale fracture system is precisely dated using chalk lithostratigraphy correlations within the basin. Moreover, an inversion method is used on fault slip data to evidence a paleostress chronology in the Anglo-Paris basin. Three main older extensive events, characterized by normal faults and jointing are recorded in Normandy and two younger compressive and extensive events with strike-slip and normal faults appear in Sussex. Paleostress records vary on each part of the eastern English Channel. The meso-scale fracture system is thus used to better define the type of relationship between meso-scale and large-scale brittle deformation in the Chalk during Meso-Cenozoic. A first NE-SW extension is recorded in Normandy in relation with local anticlines structures and related to the Lower Rhine graben opening. A second event is a WNW-ESE extension of local origin in relation with the subsidence axis of the Paris basin. The third event is a NNE-SSW extension, well marked in Normandy and related to the activation of E-W normal faults in the western approaches of the English Channel. This event is also recorded in Sussex and reactivates locally older fractures in strike-slip. The Oligocene N-S compression / E-W extension related

to the Pyrenean tectonics and the last E-W extension relative to the North Sea graben opening are well recorded in Sussex, but not in Normandy. Recent far-field stresses developed in the NW European platform are focused on deep crustal structures like the Artois hills and the Cotentin areas in France. These structures act as a stress barrier by protecting the Normandy Chalk from recent far-field stresses. On the contrary, recent far-field stresses are easily recorded by meso-scale brittle deformation on the folded Chalk in Sussex.



BOREHOLE IMAGES FOR ASSESSING PRESENT DAY STRESSES

Arnaud Etchecopar[1], Tetsushi Yamada[1] and Philip Cheung[1]

[1] Schlumberger Riboud Product Center, Clamart, France

Data usable for assessing precisely the present day state of stress are not numerous and often quite expensive to acquire. Damage observed at borehole wall is certainly one of the most interesting ways to constrain the present day state of stress. The number of wells in which a high quality image is available is now huge in many basins. However interpreting such an image in terms of stress is not straightforward. This is firstly because it is often difficult to differentiate stress induced damage from drilling damage or natural features. Secondly it is easy to assess the main stress orientations in vertical wells but the relation of the damage orientation to stress in deviated well brings much more information on the stress tensor. This presentation will address these two points.

1. The precise sorting and measurement of stress induced features all along the borehole wall when an ultrasonic image is available.
2. The determination of the stress regime and of the shape of the stress tensor from breakouts or induced fractures orientation in deviated wells.

The most well known stress induced damage is the breakouts and the induced fractures that are used for determining the stress orientation when the well is vertical. An ultrasonic image provides a precise topography of the wellbore and the curvature analysis of this topography allows sorting the breakouts from the drilling artifacts and determining the exact geometry all along the well and not only in a few places. In many wells this process indicates a strong and clear variation of the stress magnitude with respect to the lithology. This process also detects slips at preexisting planes even when they are reamed by further drilling operations. In sedimentary basins wells located far away from faults usually exhibit very regular stress distribution. On the contrary in wells crossing a fault, ultrasonic images clearly delineate the damage evolution in the vicinity of the fault plane. This evolution that reflects the stress one depends much more on the defects of the fault plane than on the average orientation of the fault itself. This makes very difficult predicting borehole stability at the fault crossing.

Another way to constrain the local state of stress is to consider the orientation of the stress induced feature alignments at deviated borehole wall. The azimuth of breakouts or induced fractures relative to the borehole axis of a deviated well brings exactly the same stress information as a slickenside on a fault plane. Deviated wells that become more and more frequent, particularly offshore, constitute the best source of information on the stress regime and on the shape of the stress tensor. Combination of this shape with mini-frac measurements or fracture reactivation allows determining the full stress tensor. But even when no direct stress measurement is available, knowing the stress regime and shape, makes possible to estimate the stability risks according to the well deviation and azimuth.

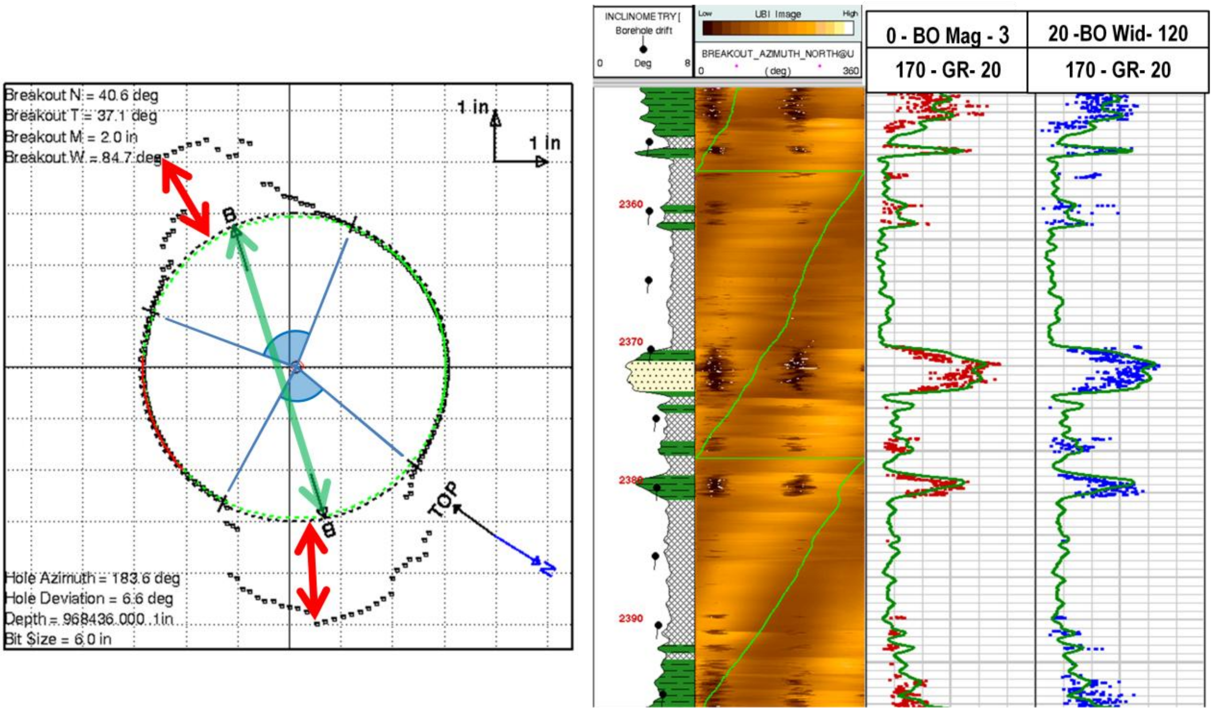


Figure-1 Breakout delineation based on a continuous analysis of the borehole curvature

- Left: Breakout measurement Azimuth (green), Amplitude (red), Width (blue)
- Right: perfect fit between the breakout geometry and the lithology

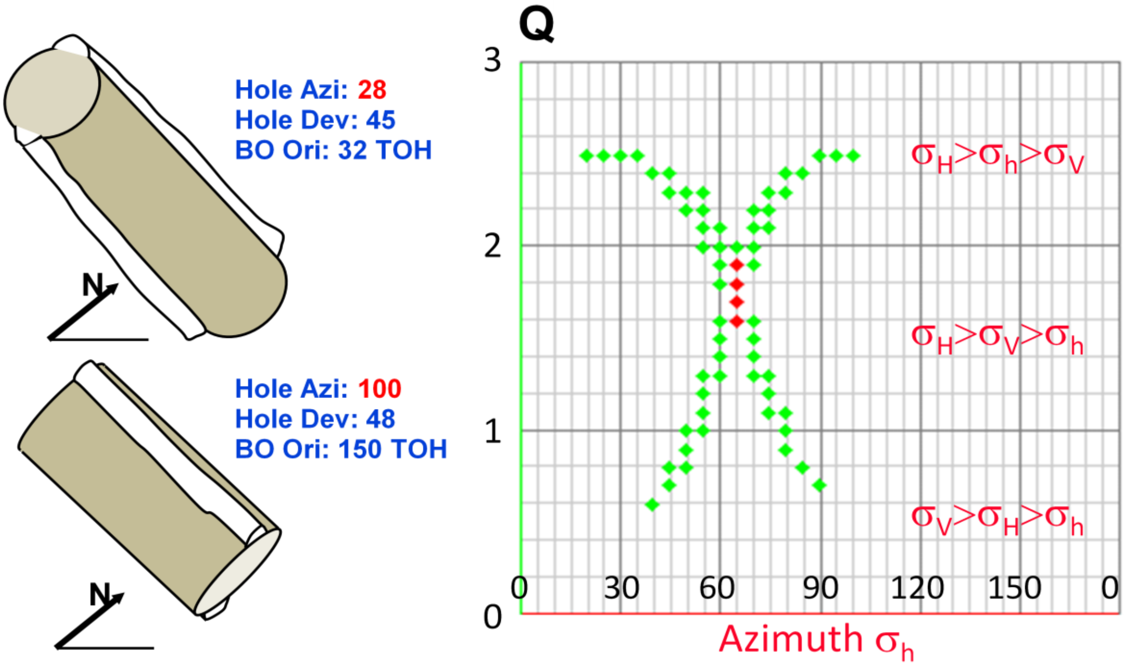


Figure-2 Stress regime and shape deduced from the breakout orientation in two deviated wells

Q is a combination of which stress is vertical with the shape factor R= $(\sigma2-\sigma3)/(\sigma1-\sigma3)$

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés

****

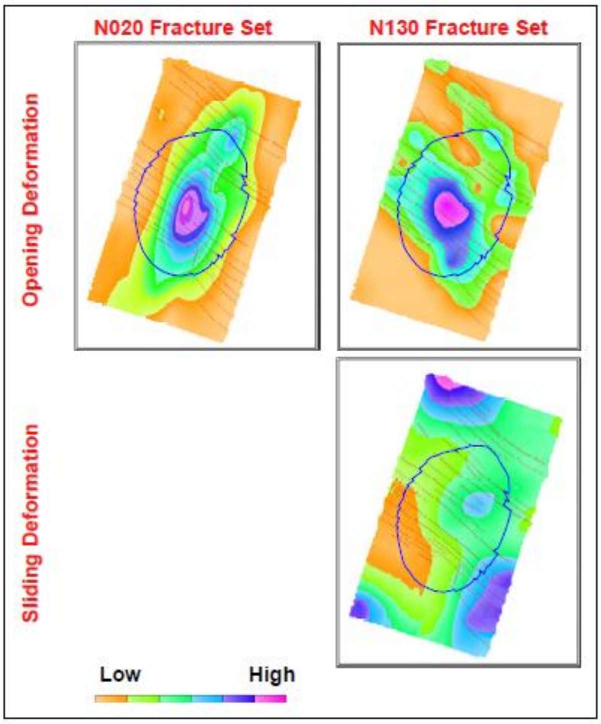
THE CHARACTERIZATION OF A FRACTURED RESERVOIR: A MULTI-DISCIPLINARY APPROACH WITH APPLICATION TO AN OFFSHORE ABU DHABI CARBONATE RESERVOIR

B. D.M. Gauthier[1], M. Guiton[1,2] and M. Garcia[3]

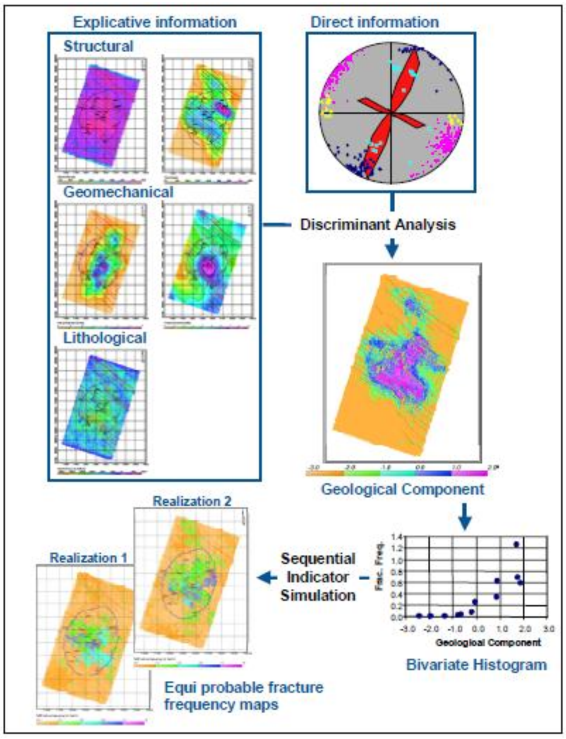
1: TOTAL, Paris La défense; 2: IFP Energie Nouvelle, Rueil Malmaison; 3: Kidova, Chaville

This study illustrates a systematic work flow for the characterization of fractured reservoirs. It begins with a structural analysis of seismic and well data which defines a structural style and fracture model for the field under study. This model is evaluated with a geomechanical approach which verifies that all mechanical conditions are full-filled. Then, all the parameters which are known to control the fracture activation and propagation are integrated through a full field fracture distribution geostatical method. Finally, the role of the present day stress field upon fracture permeability is addressed.

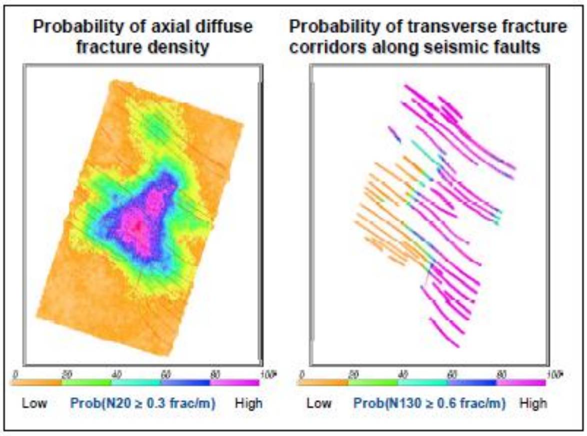
The studied Middle East carbonate reservoir is a salt related dome. Pre-existing NW-SE fractures controlled the doming event and imposed a strong mechanical heritage. The fracturing which is presently observed is mainly related to this doming event. Two mains fracture systems are observed. NW-SE pre-existing fractures were re-activated as normal faults and associated fracture corridors. The localization of the faults is controlled by deep basement lineaments and by the opening and sliding deformations associated to the doming process. Fault related fracture corridors are mainly related to the sliding deformation. NE-SW fractures, activated as new fractures during the doming, are related to both the curvature and faulting deformations and are homogeneously distributed with however a higher density at the dome crest. They were kept open after the Zagros orogeny took place. Presently, the Zagros stress field is still acting but cannot be responsible for new fracture activation. Finally, the pertinence of our fracture model is calibrated against dynamic data which qualitatively validate the model.



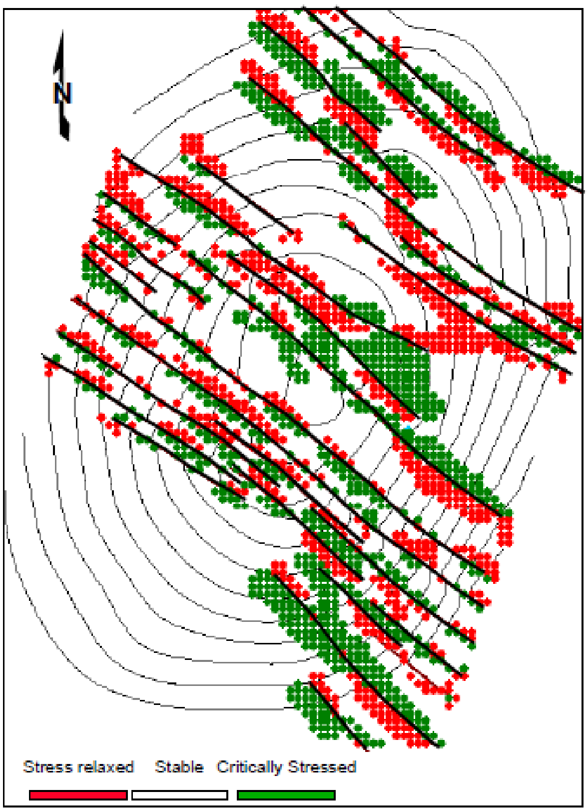
Irreversible deformation for 3D finite element modeling



Methodological flowchart of the geostatistical modeling



Present-day stress analysis of shear and tension fracture activation/reactivation.



Distribution of stress potential for fracture reactivation.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

CONFÉRENCE INVITÉE – INVITED CONFERENCE

THERMODYNAMIC ASPECTS OF THE DEVELOPMENT OF FRACTURE NETWORKS

Agust Gudmundsson[1], Nahid Mohajeri[2]

[1]Department of Earth Sciences, University of London Royal Holloway, Egham TW20 0EX, UK (a.gudmundsson@es.rhul.ac.uk)
[2]Department of Geography, University College London, Gower Street, Pearson Building, London, WC1E 6BT, UK

Thermodynamic principles form the basis for understanding fracture initiation and growth, as presented by the original Griffith crack theory. When applied to fracture networks, that is, systems of interconnected fractures, the concept of entropy is very useful. Entropy is a well-known concept from the second law of thermodynamics, but its primary use in fracture studies is through statistical mechanics and related probability distributions. Entropy for a mechanical system is related to energy principles: an isolated system that develops so as to reach equilibrium with its external and internal forces tends to attain a maximum entropy and a minimum potential energy or, in terms of fracture development, a minimum strain energy. The strain energy of a crustal segment, such as a part of a volcano-tectonic zone hosting a fissure swarm, is directly related to the mechanics of fracture development through the Griffith crack theory and its extension to modern rock-fracture mechanics. While entropy and strain energy are thus related, the possible relation of these two with the (probability) size distributions of fracture populations has received little attention. Here we show that fracture-length size distributions of 565 tectonic fractures (tension fractures and normal faults) in the active volcano-tectonic zones of Iceland follow power laws. On a bi-logarithm or log-log plot of a power law, the straight-line slope is referred to as a scaling exponent. We calculated the power-law scaling exponents and the thermodynamic (Gibbs) entropies for the length-size distributions of the 565 tectonic fractures. The fractures range in length by five orders of magnitude and belong to four networks within the active volcano-tectonics zones in Iceland.

Each network can be divided into populations based on abrupt changes (breaks) in the scaling exponents. The breaks, we suggest, are related to the comparatively long and deep fractures changing from tension fractures to normal faults and penetrating the contacts between the Holocene lava flows and the underlying and mechanically different Quaternary rocks. The results show a strong linear correlation (r = 0.81-0.93) between the scaling exponents and entropies of the fracture populations. The correlation is partly explained by the entropy (and the scaling exponent) varying positively with the length range (the difference between the longest and the shortest fracture) of the populations in each fracture network.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

LE FILON POLYMETALLIQUE DE SAINT JAQUES, MINE DE GABE GOTTES, VOSGES - CONDITIONS TECTONIQUES DE MISE EN PLACE

Yaser Hafeznia[1], Sylvain Bourlange[1] et Maryse Ohnenstetter[1]

[1] CRPG-CNRS, UPR 2300, Vandœuvre-lès-Nancy, FRANCE.

Le filon Saint Jaques de la mine Gabe Gottes appartient au système de filons minéralisés de direction E-W (N80° à N130°) du district de Sainte Marie-aux-Mines (SMM) dans les Vosges. Notre étude vise à déterminer l'origine et l'âge des circulations des fluides ayant conduit au dépôt des minéralisations métallifères. La région d'étude est affectée de plusieurs réseaux de failles mis en place lors de différentes phases tectoniques (Villemin 1986; Edel, Schulmann et al. 2007): une première phase majeure est caractérisée par des failles sénestres, de direction NNE-SSW, comme la grande faille de SMM, qui s'est formée au Carbonifère pendant l'orogenèse hercynienne. Au Permien inférieur la région a subi une extension NW-SE correspondant au jeu des failles normales NE-SW. Au Permien supérieur, la phase extension N-S à NNE-SSW a créé des failles normales de direction E-W à WNW-ESE. Toutes ces failles ont été réactivées par un régime extensif NW-SE au Lias. Un autre épisode de réactivation a eu lieu au début de l'Eocène supérieur avec une contrainte maximale orienté N-S, et minimale E-W. La réactivation des failles s'est poursuivie au début de l'Oligocène avec une extension E-W. De la fin de l'Oligocène jusqu'au Miocène inférieur, la région a subi une compression NE-SW. Les quelques mécanismes au foyer des tremblements de terre récents dans les Vosges sont compatibles avec une contrainte maximale actuelle, orientée à N30W, et une contrainte minimale, à N60E.

Dans la mine de Gabe Gottes, nous avons effectué un relevé systématique des caractéristiques de 330 failles et fractures. Six familles de failles ont été distingués selon leur orientation, leur cinématique et la nature du remplissage: 1) La premier comprend une faille sénestre apparemment plus ancienne de direction N40, 90° qui a été observée dans le travers banc, 2) une famille orientée globalement N125, 60°SW, que l'on a également observé à l'extérieur de la mine en association avec une venue magmatique (granite probablement carbonifère), 3) une famille orientée globalement N70, 54°NW, 4) une famille de failles décrochantes ENE-WSW à ESE-WNW, vraisemblablement conjuguées, les premières présentant un jeu sénestre et les secondes un jeu dextre, et qui montrent des stries superposés, particulièrement bien représentées dans le filon minéralisé de Saint Jacques, 5) une famille orientée NNE-SSW, subvertical (N27, 88°E) qui comprend des failles décrochantes dextres de travers-banc qui recoupent et déplacent le filon Saint Jacques (appartenant au groupe précédent), 6) une famille des failles orientées globalement N5, 40°E. Les failles présentant des stries nous permettent de proposer une orientation des paléocontraintes.

En fonction de la chronologie relative observée, nous avons ainsi pu rattacher les cinq différentes familles de faille aux quatre phases tectoniques précédemment décrites: 1°) La première famille qui comprend la faille sénestre N40 verticale est ainsi rattachée au Carbonifère pendant l'orogenèse hercynienne. On peut également rattacher la deuxième famille de failles aux événements tectoniques de cette période. 2°) Les failles normales de la troisième famille pourraient être rattachées à la phase d'extension NW-SE du Permien inférieur. 3°) Les stries de la quatrième famille de failles montrent les phases de réactivation des failles à l'Eocène supérieur. Une compression N-S, au début de Eocène supérieur, contemporaine du plissement alpin, produit des failles décrochantes. A partir de l'Oligocène, les contraintes changent de régime pour passer à un système extensif E-W. La contrainte principale devient verticale (stries verticales superposées aux stries horizontales de l'événement précédent). 4°) Les failles décrochantes dextres de cinquième famille peuvent être rattachées au régime compressif NE-SW du Miocène inférieur. Des fentes de tension tardives (d'après la chronologie que l'on peut construire à partir des recoupements) et orientées NE-SW pourraient correspondre à ce régime compressif.

L'histoire de la minéralisation polymétallique du filon Saint Jaques peut se résumer aux deux événements tectoniques: 1) La formation des failles E-W à WNW-ESE au Permien supérieur qui a servi de guide pour la mise en place du filon, 2) Leur réactivation aux périodes l'Eocène supérieur et l'Oligocène qui a vraisemblablement augmenté l'intensité de la minéralisation.

Références:

Edel, J. B., K. Schulmann, et al. (2007). "The Variscan tectonic inheritance of the Upper Rhine Graben: evidence of reactivations in the Lias, Late Eocene–Oligocene up to the recent." International Journal of Earth Sciences 96(2): 305-325.

Villemin, T. (1986). "La chronologie des evenements tectoniques dans le Nord-Est de la France et le Sud-Ouest de l'Allemagne du Permien a l'Actuel." Comptes Rendus - Académie des Sciences, Série II 303(18): 1685-1690.

THE USE OF MESOSCALE FAULTS AND PALEOSTRESSES IN STRUCTURAL ANALYSIS

Jean-Claude Hippolyte[1], Françoise Bergerat[2], Mark Gordon[3], Olivier Bellier[1] Nicolas Espurt[1]

[1] CEREGE, UMR 6635, Aix-Marseille University., 13545, France
[2] ISTeP, UMR 7193 CNRS-UPMC, Pierre & Marie Curie University, Case 117, 4 place Jussieu, 75252 Paris cedex 05, France.
[3] Shell International Exploration Production, Bellaire Technology Center, 3737 Bellaire Blvd., Houston, TX 77025, USA

Two of the basic assumptions in the methods of stress inversion from fault slip data are that faults slips are independent and that the stresses are uniform (e.g. Angelier, 1994). This is particularly true if deformation is low. Accordingly, the method of stress inversion from fault slip data was first applied to low deformation areas, and mainly in foreland platforms (e.g. Bergerat, 1985). There, it was attended to reconstruct the far stress fields and better understand plate tectonics. But Angelier rapidly saw that mesoscale faults and low deformation can also be found in rock volumes on plate boundaries, and the paleostress method was also successfully applied in fold and thrust belts (e.g. Barrier, 1985).

In such highly deformed areas, mesoscale fault measurement and paleostress analysis can be of useful support for structural analysis. Some examples illustrate that this approach is particularly useful for:

1) Determining the real nature of large faults.

In the Southern Apennines, paleostress analysis from mesoscale faults show that an apparently reverse fault is in fact an extensional fault that has been tilted.

In the foreland of this belt, the Mattinata fault is a large E-W strike-slip fault that cuts the Gargano peninsula. Fault slip analysis in the fault zone, and paleostress analysis outside, reveal that this supposed “sinistral” strike-slip fault mainly moved dextrally.

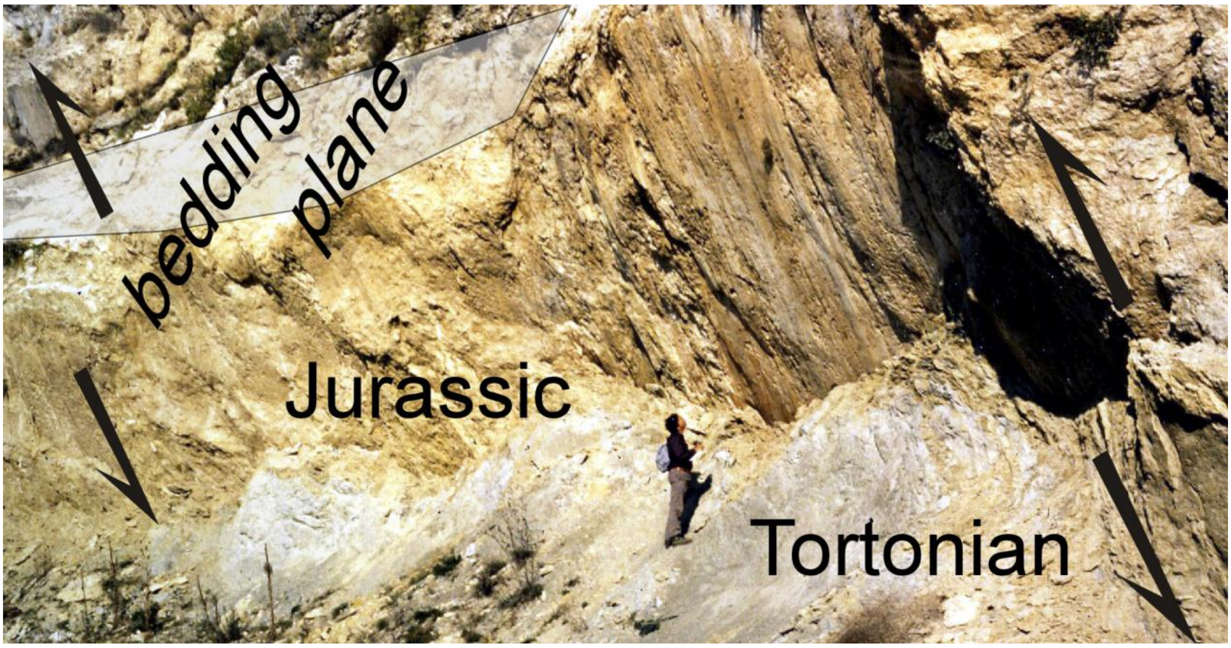
2) Determining the chronology of large structures

In Provence, the Ste Victoire Mountain constitutes an outstanding polyphase structure (e.g. Lacombe et al., 1992). Fault analysis in growth strata at the southern margin of this thrust structure shows that N-S compression was active from the Campanian to the Lutetian. The compressional structures are found to be cross-cut by Oligocene normal faults at various scales. In the Caribbean arc, cross-cutting fault relationships allowed constraining the age of the Mona Rift.

3) Determining the paleo-horizontal in conglomerates and even the direction of progradation in tilted foreset beds.

As one stress axis is commonly vertical, paleostress axes can be used for reconstructing the paleo-horizontal surface (e.g. Hippolyte et al., 1995). This is particularly useful in non-bedded rocks or in foreset beds. Near Nice, fault slip analysis and paleo-horizontal reconstructions in the foreset beds of the Vésubie Messinian canyon allow characterizing a Plio-Quaternary folding and reconstructing the Pliocene direction of progradation.

We conclude that these subsidiary applications of paleostress reconstruction should be of common use in structural geology for the important information they provide.



Angelier, J. 1994. Fault slip analysis and palaeostress reconstruction. *In:* Hancock P.L. (ed), *Continental Deformation*, Pergamon Press, 53-100.

Barrier, E., 1985. Tectonique d'une chaîne de collision active : Taiwan. Thèse Doct. Etat ès-Sciences, Univ. P.& M. Curie, Paris. 504 p

Bergerat, F., 1985. Déformations cassantes et champs de contrainte tertiaires dans la plate-forme européenne. Thèse Doct. Etat ès-Sciences, Univ. P.& M. Curie, Paris. Mém. Sc. Terre 85-07, 315 p.

Hippolyte, J-C., Angelier, J. and Barrier, E., 1995. Compressional and extensional tectonics in an arc system: example of the southern Apennines. *Journal of Structural Geology*, 17, 12, pp. 1725-1740.

Lacombe, O., J. Angelier, and P. Laurent (1992), Determining palaeostress orientations from faults and calcite twins: a case study near the Sainte-Victoire Range (southern France), *Tectonophysics*, 201, 141–156.

LATE JURASSIC TO EARLY CRETACEOUS FAULTING IN PRE-LITHIFIED SEDIMENTS, SOUTH-EASTERN FRENCH BASIN.

Catherine Homberg[1], Johann Schnyder[1], M . Benzaggagh [2], Véronique Léonardi[3]

[1] Université Pierre et Marie Curie, ISTeP- UMR UPMC-CNRS 7193, Case 129, 4 place Jussieu, 75252 Paris Cedex 05, France.
[2] Université Moulay Ismail, Faculté des Sciences, Département de Géologie, BP 11201, Zitoune, Meknès, Morocco
[3] UMR Hydrosciences Montpellier, Université Montpellier 2, Place Eugène Bataillon, 34095 Montpellier Cedex 5, France.

We present data on meso-scale normal faults cutting the Late Jurassic to Early Cretaceous sequences of the Vocontien through. These data are used to discuss the geometrical characteristics and the growth processes of faults in weakly lithified and thus very soft rocks. These faults, as well as the paleo-stresses inferred from the inversion of other small-scale faults, also highlight how the deformation scheme evolved during Mesozoic in the South-Eastern French basin. The sedimentary facies and the main rock type features of the rocks hosting the normal faults were established by a bed-by-bed field survey, completed by the examination of 28 thin-sections and datation was based on calpionellid associations. The sequences are Late Tithoninan to Valanginian in age and consist of successions of decimetre-thick micritic, homogeneous and today stiff limestone beds, sometimes separated by thin marly intervals, and scarce micro-conglomeratic beds with infra-millimetric to centimetric lithoclasts. For each fault, we measured the strike and dip of the fault planes on several sampling points, as well as the slip vector when visible. At several places, the deformation includes both offset by fault slip as well as by folding which we interpret as extensional fault-propagation folding. We measured both the offsets achieved by faulting and by both faulting and folding, referred below as the near-field and far-field displacements, respectively. The studied normal faults have maximal displacement ranging from 3 cm to 50 cm and their exposed lengths vary from 1 m to more than 3 m. Their mean strikes are NNW-SSE and WNW-ESE in the Jurassic and Early Cretaceous sequences, respectively. Within a given fault system, no significant variation in their direction are observed but changes in their dips over a short distance are common. These changes do not correspond to a fault refraction as the function of the lithology as observed in lithified multilayer systems. The variation of the fault dip occurs within a single bed so that the fault shows a curved segment with sometimes reverse dips at the top and bottom of the bed. Analysis of near-field displacement profiles indicate that these sinuous faults generally show high tip gradients up to 1 and also local gradients up to 0.3. These values are very much higher than those commonly determined in limestone sequences. For reference, a few other faults showing straight segments were analysed and they are characterized by mean gradient close to 0.04. A positive relation thus exists between the fault geometry and the local or tip gradients. The contribution of folding to the total strain is variable but can be very significant and account for 50% of the deformation. Together with the high gradient, these data show a very reduced propagation of the fault as the strain accrued.

These observations are in agreement with a fault development before complete lithification of the sediments. Our data also suggest that the direction of extension changed from a WNW-ESE to NNE-SSW direction around the Late Jurassic-Cretaceous boundary.

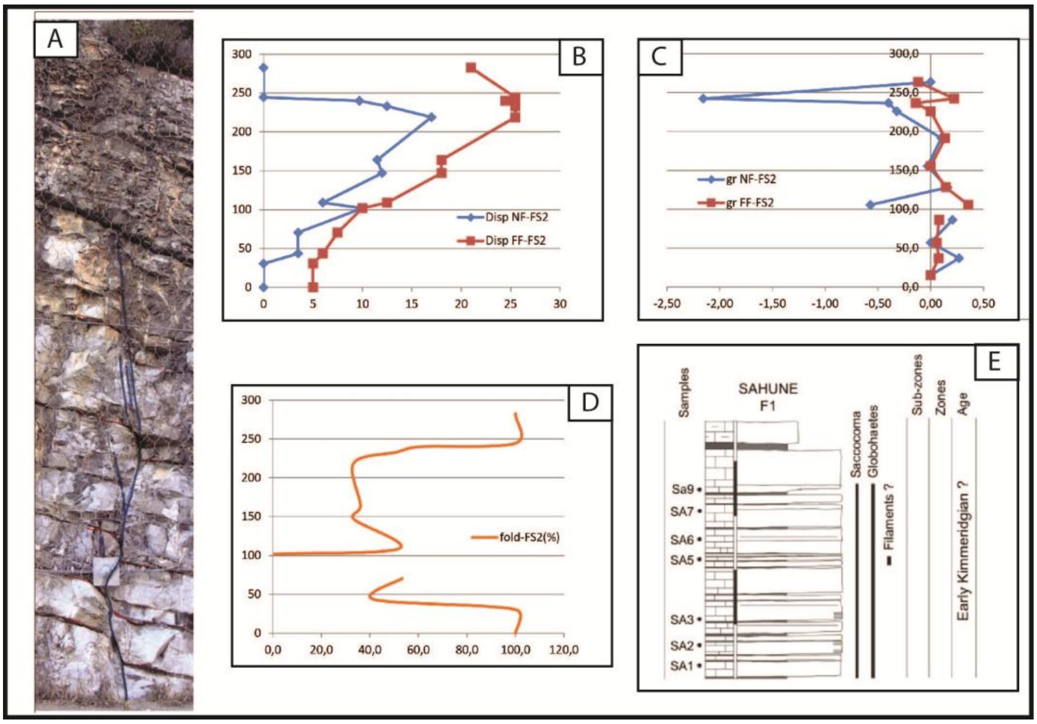


Fig. 1.Example of fault analysis at Sahune. A: Fault observed in cross-section. B, C, and D: Displacement, gradient, and folding profiles along the fault. E: Stratigraphic log of the faulted section and biostratigraphy.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

PRESENT-DAY CRUSTAL DEFORMATION IN TAIWAN OROGENIC BELT FROM CONTINUOUS GPS NETWORK FROM1995 TO 2009

Jyr-Ching Hu[1*], Kuan-Chuan Lin [1,2] Jean-Mathieu Nocquet[2], Tzay-Chyn Shin[3], Long-Chen Kuo[4], Jacques Angelier[5,6]

[1] Department of Geosciences, National Taiwan University, Taipei, Taiwan
[2]Geosciences Azur, University of Nice - Sophia Antipolis, Nice, France.
[3]Central Weather Bureau, Taipei, Taiwan
[4]Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan
[5]GEOAZUR, UMR 6526 CNRS-UNS-UPMC-IRD, Villefranche-sur-Mer, France
[6] International Laboratory « ADEPT », CNRS -NSC France-Taiwan

We collected 343 Continuous GPS stations and got precise coordination by GAMIT, YACS and QOCA from 1 January 1995 to 31 December 2009. The site position variations are investigated from velocities field, seasonal effect, coseismic and postseismic deformation of major earthquake events. First, we characterized the deformation pattern before and after the M_w=7.6 Chi-Chi earthquake of 21 September 1999 in central Taiwan. The stations of Coastal Range to Lanhsu showed the velocities are 40.1-89.1 mm/yr towards azimuth 317˚-308˚ with respect to Paisha station (S01R). The stations in the Central Range to Longitudinal Valley revealed velocities in the range 19.0-39.0 mm/yr towards azimuths 285°-318°. In the vertical velocity pattern, the significant subsidence appears in northern Coastal Range about -15.7 ±0.3 mm/yr, but the uplift in southern Coastal Range about 20.6 ±0.2 mm/yr respectively. In western Taiwan, the velocities in the inner fold-and-thrust belt range from 14.2 to 45.5 mm/yr in directions 284°-304°. The largest subsidence are occur at coastal plain(Changhua-Yunlin) about -46 ±0.3mm/yr. Extensional strain rates occur in the Ilan Plain and Pingtung plain areas at the tips of the collision belt. The largest extensional rate of our survey period was found in the Ilan Plain, with 1.21 μstrain/year in a NW-SE direction and a shortening rate of 0.24 μstrain/year in a NE-SW direction. In time series, apparent seasonal variations can be provided us to compare with the groundwater, ocean tides, atmosphere pressure and tectonic effect.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

DETERMINING THE SURFACE DEFORMATION IN ILAN PLAIN USING PERSISTENT SCATTER INTERFEROMETRY (PSI)

Chu-Chun Kang [1], Chung-Pai Chang [1,2,5], Lionel Siame[3,5] and Jian-Cheng Lee [4,5]

[1] Institute of Geophysics, National Central University, Jhongli, Taoyuan, Taiwan.
[2] Center for Space and Remote Sensing Research, National Central University, Taiwan
[3] Centre Européen de Recherche et d'Enseignement en Géosciences de l'Environnement (C.E.R.E.G.E.) – U.M.R. 6635 CNRS-INSU, Université Aix Marseille, B.P.80, Plateau de l'Arbois, 13545, Aix-en-Provence cedex 4, France.
[4] Institute of Earth Sciences, Academia Sinica, P.O. Box 1-55, Nankang, Taipei, Taiwan
[5] LIA (Associated International Laboratory) ADEPT (Active deformation and Environment Programme for Taiwan), France (CNRS/INSU) and Taiwan (NSC)

The Ilan Plain (Northeastern Taiwan) is a triangular, deltaic plain characterized by a flat topography close to the sea level, and surrounded by the high mountains of the Hsüehshan Range to the north-west, and the Central Range to the south-east. Its eastern coast faces the western tip of the Okinawa Trough (Figure a). In this study, we analyzed the present-day surface deformation of the Ilan Plain, aiming at deciphering its relationships with the regional geodynamic setting. Our approach is mainly based on surface vertical displacements revealed by Persistent Scatterers InSAR (PSI). Indeed, we combined with the previous geodetic measurements, and existing geophysical data, our PSI-derived vertical rates of surface displacement indicate that there is convincing subsidence area, located in the southern part of Ilan Plain, during the recent years (Figure b). In our opinion, the Choshui Fault is related to this process and presently borders the area of active subsidence associated with the opening of the Okinawa Trough. And provide the zipper-liked model for the propagation of the Okinawa Trough through the Taiwan mountain belt, reactivating basement faults that were originally backthrusting the Hsüeshan Range on the Central Range (Lishan-Choshui faults).

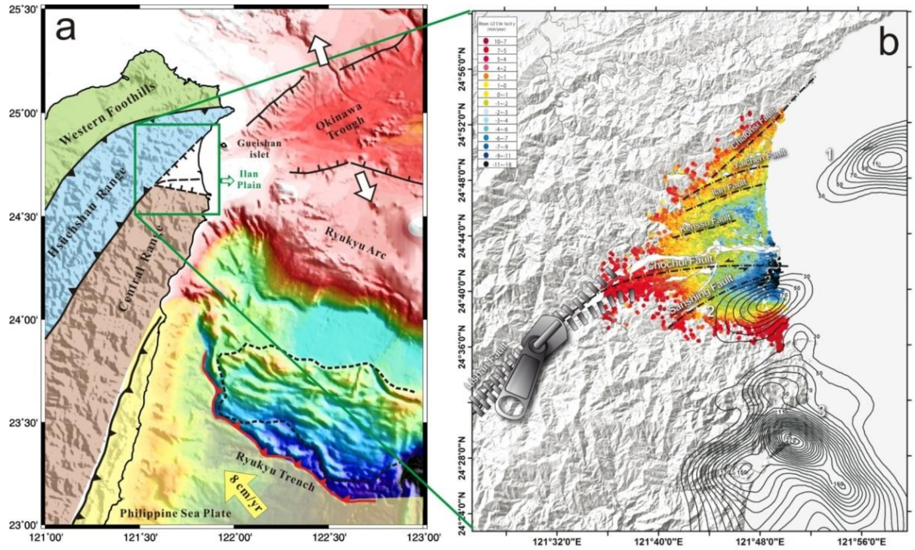


Figure (a). Tectonic framework and main structural units of northeastern Taiwan mountain belt and its connections with Okinawa Trough back-arc basin and Ryukyu arcs, accretionary wedge, and trench subduction systems. The plate convergence of the Philippine Sea Plate relative to Eurasia (eastern Taiwan) is on-going at a rate of roughly 82 mm/yr in a NW-SE direction (Yu et al., 1997; Sella et al., 2002). Bathymetry data come from Sibuet et al. (1998). (b) The zipper-liked model for the propagation of the Okinawa Trough through the Taiwan mountain belt, reactivating basement faults that were originally backthrusting the Hsüeshan Range on the Central Range (Lishan-Choshui faults). Fault traces are those mapped by Jhiang (1976) from his seismic data (modified in the northern part according to Shyu et al., 2005). The coloured points are the mean LOS velocity of the processed PS in the Ilan Plain (same legend as for figure 5). Topographic map in background is the Taiwan digital elevation model from Taiwan Forestry Bureau (resolution: 40 m per pixel). Contour lines represent the earthquake density distribution (1973-2008, Central Weather Bureau Earthquake Catalogue) with depth lower than 30 km and no magnitude cut-off. Those contour lines have been obtained by gridding the number of events with a cell-resolution of 0.5 km. This distribution map clearly evidences the seismicity patches in the area: (1) the seismicity related to the opening of the Okinawa Trough, (2) the seismicity of the southernmost area of the Ilan Plain most probably related to the Sanshing Fault described by Jhiang (1976), and (3) the seismicity patch associated to the collision zone in the Hualien area.

Hooper, A., (2008) A multi-temporal InSAR method incorporating both persistent scatterer and small baseline approach, *Geophys. Res., Lett.,* 35, L16302, doi:10.1029/2008GL034654.

Lee, J.C., Angelier, J., and Chu, H.T., (1997) Polyphase history and kinematics of a complex major fault zone of the Taiwan mountain belt: the Lishan Fault, *Tectonophysics,* 274, 97–115.

Jhiang, S.C., (1976) Seismic study of the Ilan Plain, *Mining Technical Digest,* 14(6), 215-221.

Sella, G.F., Dixon, T.H., and Mao, A., (2002) REVEL: A model for recent plate velocities from space geodesy, *J. Geophys. Res.,* 107(B4), 2081, doi:10.1029/2000JB000033.

Sibuet, J.C., Deffontaines, B., Hsu, S.K., Thareau, N., Le Formal, J.P., Liu, C.S., and the ACT party (1998) Okinawa Through basin: early tectonic and magmatic evolution, *J. Geophys. Res.,* 103, 30,245-30,267.

Yu, S.B., Chen, H.Y., and Kuo, L.C., (1997) Velocity field of GPS Stations in the Taiwan area, Tectonophysics, 274, 41–59.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

MULTI-STAGE EMPLACEMENT OF GOLD-BEARING QUARTZ VEINS FROM KALANA GOLD MINE INFERRED BY A STRUCTURAL SURVEY.

Dimitri Kusters[1], Olivier Femenias[1]

[1] Univ. libre de Bruxelles, ULB, Bruxelles, Belgium

The brittle deformation in birimian rocks at Kalana gold mine is a good indicator of the regional tectonic. Geometrical and kinematic analysis have been done for the gold deposit. Using multiple inversion methods (through MIM (Yamaji, 2000) and T-tecto 2.0 (Zalohar, 2007) software) on the heterogeneous fault population, three deformation phases have been distinguished.

The kalana gold mine is located in birimian and eburnean rocks, south of Mali. The diorite intrusion of the deposit was date to late eburnean orogeny (Gasquet, D. et al., 2003). The gold bearing structure are important quartz veins, SE-dipping and SW dipping, associated to inverse movement. Another major structures are north-south stratification of the sedimentary rocks intruded and dry fault planes. Dextral and sinistral movements are observed on those planes as well as oblique-slip (fig. 1).

The three deformations phases (fig. 2) determined by two different multiple inversion methods are coherent and observations allow to establish the chronology of the events. First, a triaxial compressive phase with σ_1 oriented N317 sub-horizontal and σ_3 sub-vertical. This phase is associated with the SE-dipping quartz veins and left strike-slip movement on north-South dry planes. The second one is also triaxial but σ_1 and σ_2 are inverted. This phase is associated with SW-dipping veins and right strike-slip movements on the North-South dry planes. The last phase is uniaxial and σ_1 is sub-vertical. It is related to the obique-slip lineation observed on the vertical planes

The geological structure of the area is mainly based on mapping and geochronological studies (Liégeois et al., 1991, Gasquet, D. et al., 2003). Because of the thick lateritic layer, the deposit is one of the few accessible outcrops. On geological map, other's intrusions are noticed. Their orientations and the granodioritic intrusion shape correspond to a riedel system in a large shear zone oriented ~N350. The shear zone is dominated by left strike-slip movement event. Right strike-slip movement is supposed (regarded to the observations) to be weaker in the same shear zone axis (fig. 3).

Fig. 1 : Plane groups : yellow =Qz veins ; blue=S_0 ; green = tension craks

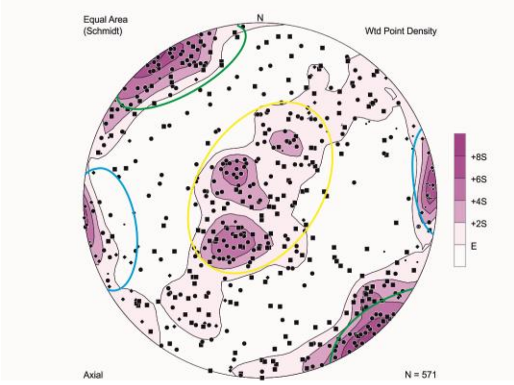
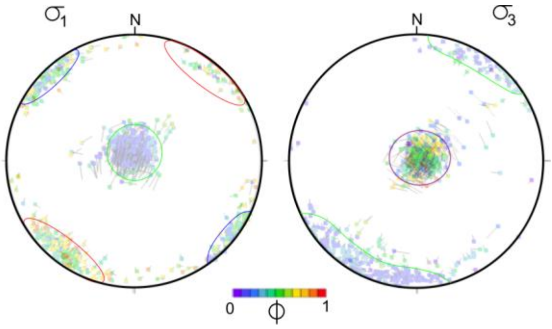


Fig. 2 : MIM-software results : stereographic projection σ_1 (left panel) and σ_3 (right panel). Three phases: 1: σ_1=N317 sub-horiz., σ_3 sub-vertical (blue) ; 2 : σ_1=N232 sub-horiz., σ_3 sub-vertical (red); 3: σ_1 sub-vertical, σ_3 is sub-horiz and sparsed



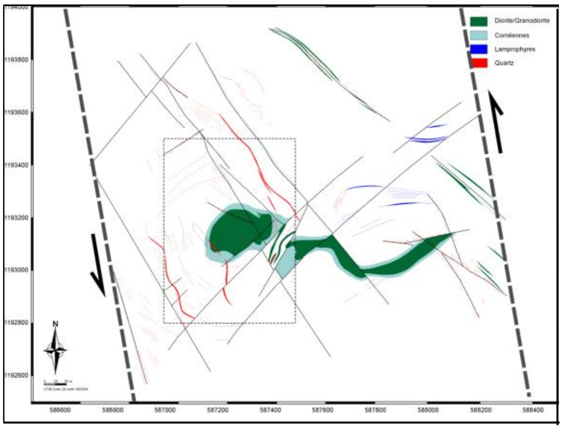


Fig. 3: Kalana area geological map (dotted square represents the mine area) with shear zone interpretation for the intrusion structure.

Gasquet , D.; Barbey, P.; Adou, M.; Paquette, J.L.;. (2003). Structure, Sr-Nd isotope geochemestry and zircon U-Pb geochronology of the granitoids of the Dabakala area (Côte d'Ivoir): evidence for a 2.3 Ga crustal growth event in the Paleoproterozoic of West Africa? *Precambrian Research*(127), 329-354.

Liégeois, J., Classens, W., Camara, D., & Klerkx, J. (1991). Short-lived Eburnian orogeny in Southern Mali. Geology, tectonics, U-Pb and Rb-Sr geochronology. *Precambrian Research*(50), 111-136.

Yamaji, A. (2000). The multiple inverse method: a new technique to separate stresses from heterogeneous fault-slip data. *Journal of Structural Geology, 25*, 241-252.

Zalohar, J., & Vrabec, M. (2007). Paleostress analysis of heterogeneous fault-slip data: The Gauss method. *Journal of Structural geology*(29), 1798-1810.

This research was funded by IAMGOLG Corporation.

WHICH TECTONIC REGIME PREVAIL EAST OF TAIWAN ?

Serge Lallemand[1], Thomas Theunissen[2], Yvonne Font[3], and Chao-Shing Lee[4]

[1] Géosciences Montpellier, CNRS, Université Montpellier 2
[2] IRAP, OMP, Toulouse
[3] GéoAzur, IRD, UNSA, Villefranche/Mer
[4] NTOU, Keelung, Taiwan

The offshore region east of Taiwan exhibits a variety of tectonic regimes both in space and through time, so that their deconvolution from structural archives or seismic expression is not an easy task. Firstly, the southernmost segment of the Ryukyu trench is located at the place of the former northern passive margin of the South China Sea. Secondly, the passive margin was reactivated into an active one during the last 8 m.y., and thirdly, it underwent collision between the northern Luzon volcanic arc and the Chinese platform before to rift again as the result of back-arc extension produced by trench roll-back. Once the trench-arc-back-arc system was set, one might expect classical tectonic regimes within the converging lithospheres ... which is not the case !

Active and passive seismic experiments (RATS) were conducted in 2008 and 2009 in this region in order to better image and characterize active faulting. Earthquake focal mechanisms indicate sharp changes over short distances in the offshore region just east of the northeast coast of Taiwan. Background seismicity and crustal structure both indicate strong deformation of the Philippine Sea plate edge when subducting beneath NE Taiwan, as well as active faulting within the overriding plate. Most of the seismicity in the Taiwan region is concentrated in the offshore area east of Taiwan. We were able to identify several active faults able to trigger M7 or M8 earthquakes.

LE SEISME ET LE TSUNAMI DU 23 FEVRIER 1887 SUR LA COTE LIGURE (MEDITERRANEE OCCIDENTALE) : OU EST LA FAILLE ?

Christophe Larroque[1], Oona Scotti[2] et Mansour Ioualalen[3]

[1] UMR Géoazur 6526, CNRS-IRD-UPMC-UNS-OCA, 250 Rue A. Einstein, 06560 Valbonne, France.
[2] Institut de Recherches et de Sûreté Nucléaire, BERSSIN, B.P.17, 92262 Fontenay-aux-Roses, Cedex, France.
[3] Institut de Recherche pour le Développement, IRD, UMR Géoazur 6526, CNRS-IRD-UPMC-UNS-OCA, La Darse, BP 48, 06235 Villefranche-sur-mer Cedex, France.

Le matin du 23 Février 1887, un séisme majeur a secoué les villes et villages de l'ensemble de la Riviera française et italienne. Cet événement destructeur provoqua la mort de plus de 600 personnes et de très nombreuses destructions entre Menton et Imperia. Le séisme fut suivi par un tsunami dont le run-up atteignit 2 m dans la zone d'Imperia.

Le séisme « Ligure » s'est produit à la jonction entre les Alpes du Sud et le bassin Ligure (Larroque et al., 2009). Pour un événement historique tel que celui-là, l'épicentre, la magnitude équivalente et la faille responsable sont difficiles à caractériser avec précision. Les récentes campagnes de géophysique marine « MALISAR » ont permis d'identifier un système de failles inverses actives de direction N60-70°E et long d'environ 80 km au pied de la marge nord-Ligure (Figure 1; Larroque et al., 2011). Nous proposons que la rupture de segments appartenant à ce système de failles nord-Ligure, connecté à un plan de chevauchement à faible pendage vers le nord soit la source du séisme de 1887.

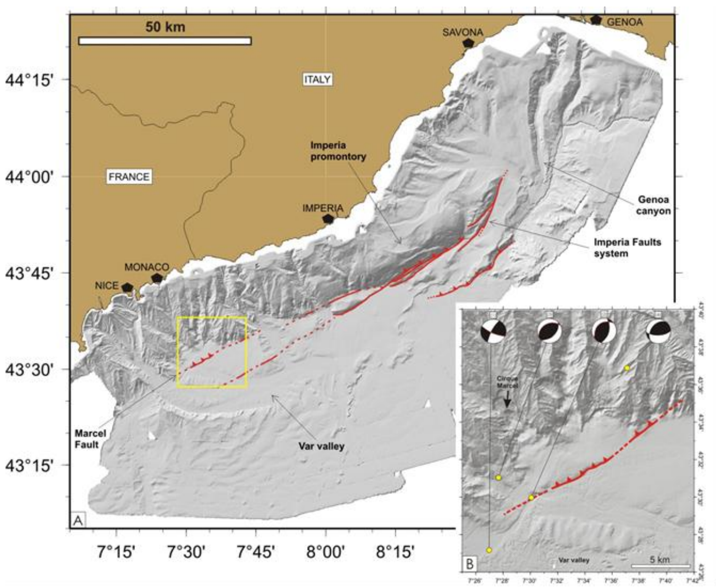


Figure 1: A, Structural sketch of the northern Ligurian Faults system. Several faults oblique to the margin direction, run 80-km long from Nice to Savona. B (inset: yellow rectangle), focal mechanisms of the moderate earthquakes associated with the Marcel Fault. (1) 1 May, 1986, ML =3.8; (2) 26 December, 1989, ML =4.5; (3) 25 February, 2001, ML =4.6; (4) 21 April, 2009, ML =3.0.

Nous avons analysé les données sismologiques des bases macrosismiques SISFRANCE-2008 et DBMI-2004 (Italie) avec plusieurs modèles d'atténuation d'intensité et de profondeur focale. Les résultats indiquent une localisation en mer de l'épicentre (latitude [43.70°-43.78°N] et longitude [7.81°-8.07°E]) avec une magnitude Mw comprise entre 6,3 et 7,5.

Les données hydrologiques (observation et modélisation du tsunami) ont été utilisées pour affiner l'intervalle de magnitude et déterminer la cinématique de la faille. De nombreux scénarios de source sismique ont été testés. Sept ont été retenus et discutés en détail (Larroque et al., soumis) pour un séisme superficiel se produisant sous la marge nord-Ligure. L'observation principale est le marégramme du port de Gênes pour lequel les statistiques basiques ont été réalisées sur l'enregistrement et la simulation avec une analyse en harmonique simple (caractéristiques du spectre d'onde).

Cette analyse indique que les résultats cohérents sont obtenus avec une faille inverse de direction N55°E et une magnitude Mw de l'ordre de 6,8-6,9. Les 2 meilleurs scénarios correspondent également à un plan de faille penté à 70° vers le Sud ou à 16° vers le Nord à une profondeur de 15 km. En prenant en compte la localisation de l'épicentre macrosismique et l'évolution morphotectonique de la pente continentale nous proposons que le séisme « Ligure » correspond à l'activation d'une faille inverse de direction N55°E à pendage nord avec un déplacement co-sismique de 1,5 m (Figure 2).

Larroque, C., Delouis, B., Godel, B. & Nocquet, J.M., 2009. Active deformation at the southwestern Alps – Ligurian basin junction (France-Italy boundary): Evidence for recent change from compression to extension in the Argentera massif. Tectonophysics, 467, 1-4, doi:10.1016/j.tecto.2008.12.013

Larroque, C., Mercier de Lépinay, B. & Migeon, S., 2010. Morphotectonic and fault-earthquake relationships along the northern Ligurian margin (Western Mediterranean) based on high resolution multibeam bathymetry and multichannel seismic-reflection profiles. Marine Geophysical Researches, doi:10.1007/s11001-010-9108-7

Larroque C., Scotti O. & Ioualalen M., 2011. Reappraisal of the 1887 Ligurian earthquake (western Mediterranean) part I: characterization of the event. Submitted to Geophysical Journal International.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

ARCHITECTURE AND SLIP BEHAVIORS OF A PLATE BOUNDARY MEGA-THRUST: A CASE STUDY OF THE LONGITUDINAL VALLEY FAULT SYSTEM IN EASTERN TAIWAN

Jian-Cheng Lee[1], Jacques Angelier[2], Hao-Tsu Chu[3], Chung-Hsiang Mu[1, 4], Chia-Yu Chen[1, 5], Shu-Hao Chang[1], Wen-Jeng Huang[4], Horng-Yue Chen[1]

[1] Institute of Earth Sciences, Academia Sinica, P.O. Box 1-55, Taipei, Taiwan
[2] Observatoire Océanologique de Villefranche, Géosciences Azur, France
[3] Central Geological Survey, Taipei, Taiwan
[4] Department of Earth Sciences, National Central University, Chungli, Taiwan
[5] Department of Geosciences, National Taiwan University, Taipei, Taiwan

The 180-km-long Longitudinal Valley represents the plate suture between the converging Philippine and Eurasian plates in eastern Taiwan. We combined geological surface investigation, geodetic measurements at the different time-and-space scales, and seismological data to illustrate the fault system of the Longitudinal Valley, which is composed of a few fault patches, each with its own fault geometry and slip behaviors. From the regional point of view, the Longitudinal Valley fault system (LVF) can be roughly divided into northern, central and southern parts. Furthermore, the northernmost and southernmost tips also showed rather unique styles of deformation and fault kinematics. The northern part of the LVF is characterized by a northward moving hanging-wall block of the northern Luzon arc, which is beginning to subduct beneath northern Taiwan. As a result, the northern LVF shows a dominant left-lateral strike-slip movement, however, seemingly fully locked in the last decades. The central part of the LVF can be distinguished to two active fault segments: the 40-km-long Yuli fault to the north and the 35-km-long Chihshang fault to the south. The Yuli fault, which has produced a historical M 7.1 earthquake in 1951, is likely of a longer recurrent time with a larger magnitude of earthquakes compared to the Chihshang fault, which has produced two M 6.2-6.5 earthquakes in 1951 and 2003 during the last one hundreds years. Interesting, both Yuli and Chihshang faults reveals a vigorous surface creep with a dominant thrusting at a rate of 3 cm/yr during the last decades. The southernmost LVF is characterized by two parallel branches of thrusts, separated by a 5-km-wide block of Quaternary fluvial deposits of 1-2 km thick. In addition to a

west-vergent LVF system, there seemingly exists an opposing east-vergent thrust system on the other side of the Longitudinal Valley. However, this thrust remains questionable with likely discontinuous segments and no direct evidence from surface outcrops.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

ROCK MAGNETIC STUDY OF FAULT GOUGE MATERIALS FROM 1999 CHICHI EARTHQUAKE AND 2008 WENCHUAN EARTHQUAKE

Teh-Quei Lee[1], Yu-Min Chou[2], Shern-Rong Song[2], Charles Aubourg[3] and Hai-Bin Li[4]

[1] Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan
[2] Department of Geosciences, National Taiwan University, Taipei, Taiwan
[3] Laboratoire des Fluides Complexes et leurs Resevoirs, Université de Pau et des Pays de l'Adour, Pau, France
[4] Institute of Geology, Chinese Geological Academy, Beijing, China

This study presents the magnetic results of fault gouge materials taken from TCDP-B hole at the depth of 1136 m in Taiwan and the trenching site of Wenchuan earthquake located at Geolong (near Peichuan), Sichuan in China. Magnetic analyses including magnetic susceptibility, thermomagnetic analysis, saturation isothermal remanent magnetization (SIRM), low temperature magnetic measurement, hysteresis loops, …etc. were analyzed.

Rock magnetic results of the fault gouge of TCDP-B hole indicated that the principal slip zone (PSZ) of the ChiChi earthquake located at 1136.38 m within the black gouge zone, which dominated the highest magnetic susceptibility in the fault gouge zone but not with the highest SIRM. The major magnetic mineral is neo-formed single domain (SD) magnetite. The highest SIRM was found to be about 3-4 cm above the PSZ which dominated neo-formed goethite as the major magnetic mineral. It is thought that the PSZ was in the reducing environment but the other was not during the earthquake occurred.

The fault gouge at the Geolong trenching section could be divided into three portions: the gray-black gouge, the greenish-gray gouge and the yellow-red gouge. The PSZ of the 2008 main shock of the Wenchuan earthquake was not found yet. Rock magnetic results indicated that at least three different components of pyrrhotite dominated in the gray-black gouge zone with relatively less abundance of magnetite. The other gouge zones also dominate the same magnetic minerals as the gray-black gouge, but some minor oxidized magnetic minerals, such as hematite, goethite etc., could also be identified. It is said that the gray-black gouge zone was in a relative reducing environment. Thus, our rock magnetic results suggest that the PSZ of the Wenchuan earthquake could be delimited in the gray-black gouge zone probably.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

THE NORTHWARD MIGRATION OF THE MARMARA FAULT

Xavier Le Pichon[1], Caner Imren[2], Claude Rangin[1], Celal Sengor[2] and Muzaffer Siyako[3]

[1] Collège de France, Aix en Provence
[2] Istanbul Technical University, Istanbul
[3] T P A

We give evidence that the story of the NAF in the Marmara Basin is one of progressive northeastward migration of the strike-slip motion. Subsidence occurs to the north of the main strike-slip motion zone. Then the strike slip motion migrates northward within the thinned subsiding zone. Thus, as the migration progresses, the partition of motion between the northern and southern branch transfers most of the strike-slip motion to the north. We conclude that this branch of the NAF has migrated to the N probably in three stages between 5 Ma and the present.

The southernmost branch (branch 1) of the NAF, still active today, was activated in Serravallian time, about 10-11 Ma. Shortly later, a large rift was initiated over the present southern shelf of the Marmara Basin, to the north of this southern branch. This may have been the time at which the detachment that thinned the southern portion of the Marmara basin (Bécel et al., 2009) was activated. In Lower Pliocene, possibly 4 Ma, a continuous branch (branch 2) of the NAF extended for the first time over the whole width of the southern Marmara basin, from the Gemlik Gulf to the Dardanelles Straits within this rift. It was forced to bypass the Marmara Island Eocene block through a fairly strong curvature. This curvature resulted in strong compression to the west probably responsible for the formation of the folds described by Armijo et al. (1999) as due to the Ganos fault. This Marmara southern Shelf branch was deactivated about 3 Ma.

The present northern active branch (branch 4) is probably less than 1 Ma, and this suggests that there was an intermediate stage (branch 3) between 3 and 1 Ma. It is at this stage that the Ganos fault would have been initiated. These results have an implication for the present seismogenic pattern. This is because the southern branches are not completely deactivated. Within the Gemlik basin, Gasperini and Polonia (2009) found 5 mm/yr of dextral strike slip. Thus the Armutlu peninsula is situated between two active branches of the NAF, which explains why Armutlu is rotating clockwise.

GOUGE COMPACTION AS A SOFTENING PROCESS. CLUES FROM ANALYTICAL SOLUTION AND 2D MECHANICAL MODELLING.

Laetitia Le Pourhiet[1], Emmanuel Lecomte[2] and Olivier Lacombe[1]

[1] Univ. Pierre et Marie Curie, ISTEP, Paris, France
[2] Heriot-Watt University, Edinburgh, Scotland

The existence of active low angle normal faults is much debated because (1) the classical theory of fault mechanics implies that faults are locked when the dip is less than 30°and (2) shallow dipping fault planes do not produce large earthquakes (M > 5.5). However, a number of field observations suggest that brittle deformation occurs on low angle normal faults at very shallow dip.

To reconcile observations and theory, we use an alternative model of fault reactivation including a thick elasto-plastic frictional fault gouge. We first develop analytical solution for small strain that predicts both the amount of slip and the slip line within the fault gouge. In a second part, we test the model at large strain by the mean of 2D mechanical modeling.

We show that plastic compaction allows reducing the friction of faults sufficiently for low angle normal faults to be active at dip of 20°. As the model predicts that these faults must be active in a slip-hardening regime, it prevents the occurrence of large earthquakes. However, we also evidence the neoformation of Riedel shears within the thick fault zone, which we postulate may be responsible for repeated small earthquakes and we apply the model to the Gulf of Corinth (Greece).

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

CONFÉRENCE INVITÉE – INVITED CONFERENCE

A CRITICAL LOOK AT THE WALLACE-BOTT HYPOTHESIS IN FAULT-SLIP ANALYSIS

Richard J. Lisle[1]

[1] School of Earth and Ocean Sciences, Cardiff University, Cardiff CF10 3AT, UK

The assumption that incremental slip on faults occurs in the direction of the maximum resolved shear stress on the fault plane forms the basis of several methods of analysis in the fields of seismology and structural geology. Wallace (1951) and Bott (1959) used this assumption as a starting point in their pioneering work on the relationship between faulting kinematics and the ambient stress tensor, and the assumption has become known as the Wallace-Bott hypothesis (Angelier1994).

The paper examines several issues that have a possible bearing on the validity of the Wallace-Bott hypothesis:

1) The **shear stress variation** with direction on the fault plane plots as a circle in polar co-ordinates. The curve has therefore low peakedness (Fig 1) so that shear stress is high within an angular range of +-26°.

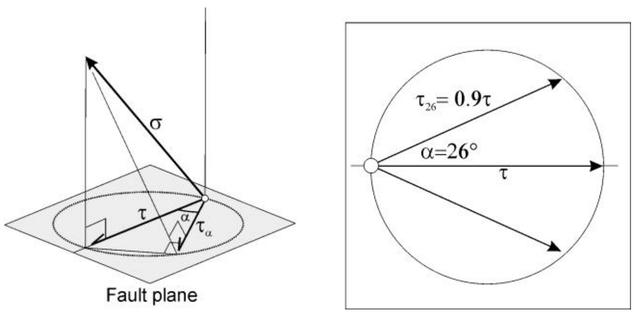


Fig.1: Shear stress variation on the fault plane; (a) the stress vector σ resolved along different directions produces a circular plot in polar coordinates, (b) the range of directions having resolved shear stress greater than 90% of maximum value is +-26°

2) **Intersecting faults**: Bulk brittle deformation accommodated by simultaneous movement of differently faults requires a kinematic compatibility between intersecting faults that is at odds with the Wallace-Bott hypothesis.

3) **Non-planar faults** pose problems for the hypothesis because simple displacement /rotation of rigid wall rocks may not agree with the resolved shear directions at different points on the fault surface may be. For example a thrust with flats and oblique ramp cutting anisotropic bedded sequences would expect to lead to slip directions that maintain a constant angle with the ramp axis (Fig 2). Such slip patterns do not accord with the Wallace-Bott hypothesis.

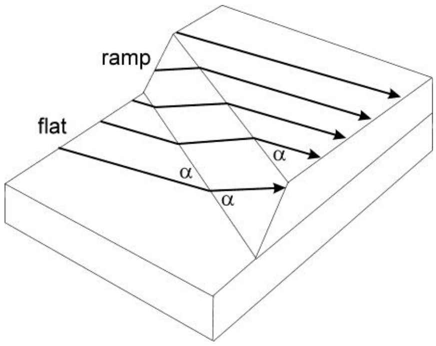


Fig. 2: A non-stretching hangingwall of a thrust fault will constrain slip directions to maintain a fixed angle with respect to the axis of ramp.

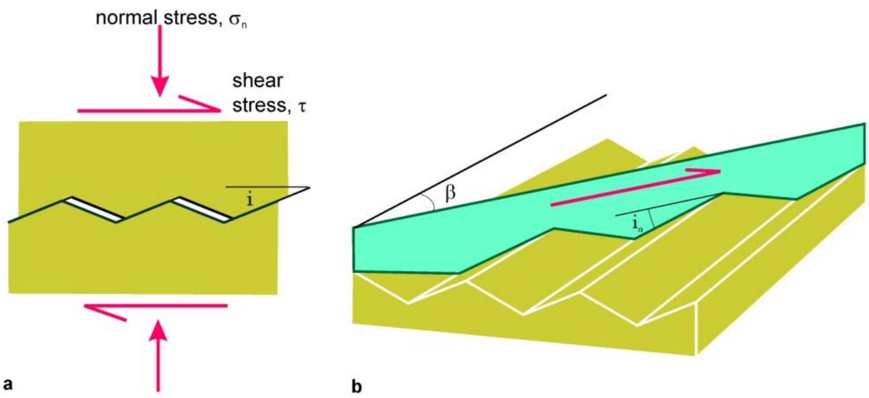


Fig. 3: a) Normal and shear stress acting on a corrugated fault. The shear strength of the fault depends on the normal stress, tha angle of friction and the angle of inclination of the flanks of the corrugation i with respect to the average orientation of the fault surface. B) Slip in a direction at an angle β with respect to the axes of the corrugation. The effective ramp angle in this oblique direction equals the apparent inclination angle i_a.

4) **Corrugation structure**, common on many fault surfaces, leads to an anisotropy of their shear strength. Using simple models of the fault surface geometry, it is possible to quantify the magnitude of this anisotropy.

The anisotropy deflects the fault's slip direction away from the direction of maximum shear strength, and can in some cases completely constrain the slip direction ("tramlining"). This effect is most pronounced under low normal stress conditions.

5) **Faults linking non-conservative structures**, e.g. transforms and faults connecting stylolitic surfaces, show linear structures with orientations that do not match those expected from the Wallace-Bott assumption.

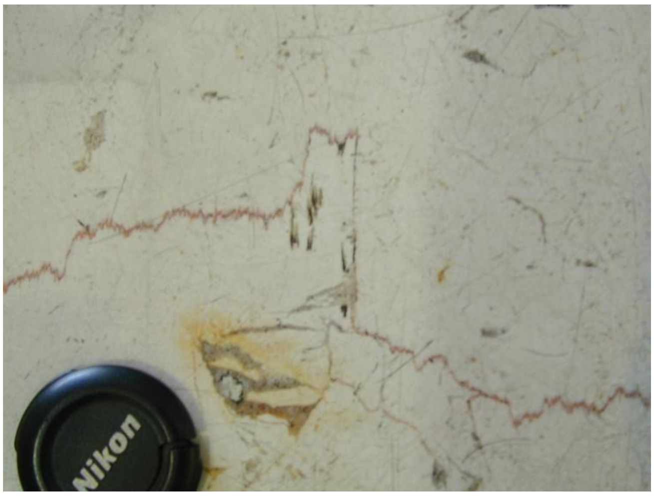


Fig. 4: "Transform-like" structure connecting stylolitic surfaces.

Conclusions: The Wallace-Bott approach assumes the rock mass to be a continuum. The presence of planes of weakness leads to complications involving compatibility of kinematics on single faults and between intersecting faults

References

ANGELIER J. (1994).- Fault slip analysis and palaeostress reconstruction. *In*:

HANCOCK P.L., Ed., Continental Deformation, Pergamon Press, Oxford, 419 p.

BOTT M.H.P. (1959).- The mechanics of oblique slip faulting. – *Geological Magazine*, 96, 109-117.

WALLACE R.E. (1951).- Geometry of shearing stress and relation to faulting. – *Journal of Geology*, **59**, 118-130.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

COMPARISON BETWEEN TAIWAN AND LONGMENSHAN MOUNTAIN BELTS

Chia-Yu Lu[1], Chih-Tung Chen[1], Kuo-Jeng Chang[2], Rou-Fei Chen[3,4,] Jun Ding[5], Guitang Pan[5], Jian-Zhong Li[5], Yuping Liu[5] , and Fuguang Ying[5]

[1]Department of Geosciences, National Taiwan University
[2]Department of Civil Engineering, National Taipei University of Technology
[3]Institute of Earth Sciences, Academia Sinica
[4]Department of Geology, Chinese Culture University
[5]Chengdu Institute of Geology and Mineral Resources

In Taiwan today, the subduction of the Chinese continental margin under the Luzon arc results in the progressive growth of an active orogenic wedge. It is one of the best places to study the complex relationships that occur between the tectono-metamorphic processes controlling deformation (plate rheology and kinematics) and surface processes (erosion and sedimentation). High topography in central Asia is perhaps the most fundamental expression of the Cenozoic Indo-Asian collision, yet an understanding of the timing and rates of development of the Tibetan Plateau remains elusive. On the other hand, the eastern margin of the Tibetan Plateau is marked by an extremely steep mountain front with relief of over 5 km. This topography, coupled with abundant Mesozoic thrusts within the margin, explains why tectonic maps of the India-Asia collision typically show the eastern margin as a major thrust zone, and attracting abundant geologists and scientists working with. The surface rupture zone generated by the Wenchuan earthquake and aftershocks are distributed along the NE-trending Longmenshan tectonics belt. This tectonic belt composed of three boundary faults, named the Mao-Wen fault, Yingxiu-Beichuan fault and Anxian-Guanxian fault respectively. The Wenchuan earthquake demonstrates again its high tectonic activities in this area. The Sichuan basin, the flat area (Chengdu plane) is dense population and heavy of industry, the tectonics activity and geological hazard within this area basin becomes a major concerns. In this study, the deformation activities around the foreland basin area will re-examined by means of morphotectonics, geochronology and model modeling etc., in order to decipher the tectonic activity around the foreland area.

PALEO-STRESS INVERSION USING A FULL MECHANICAL SCENARIO AND MULTIPLE TYPES OF DATASET

Frantz Maerten[1] and Laurent Maerten[1]

[1] Schlumberger Montpellier Technical Center (MpTC), Grabels, France.

Methods for stress inversion, using measured striations and/or throw on faults, are mainly based on on the assumptions that: (i) the stress field is uniform within the rock mass embedding the faults (assuming no perturbed stress field), and that (ii) the slip on faults has the same direction and sense as the resolved far field stress on the fault plane. However, it has been shown that slip directions are affected by: (i) anisotropy in fault compliance caused by irregular tip-line geometry; (ii) anisotropy in fault friction (surface corrugations); (iii) heterogeneity in host rock stiffness; and (iv) perturbation of the local stress field mainly due to mechanical interactions of adjacent faults. Mechanical interactions due to complex faults geometry in heterogeneous media should be taken into account while doing the stress inversion. Determining the parameters of such paleostress in the presence of multiple interacting faults requires running a lot of simulations, and therefore a huge amount of computation time in order to fit the observed data.

Here, we investigate this approach with a 3D boundary element method using the principle of superposition that applies to linear elasticity for heterogeneous, isotropic whole-of half-space media. Given some measures of the fault throw, dip-slip and/or slickenline directions, stress measurements, breakout orientation, micro seismicity, faults geometry, GPS and InSAR data, fold axis, focal mechanisms, fractures orientation (joints, veins, dikes, pressure solution seams with stylolites) or secondary fault plane orientations, we recover for the remote stress state for multiple tectonic events in a fast way.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

IMPACT OF SURFACE PROCESSES ON ACTIVE FAULTING IN TAIWAN.

Jacques Malavieille[1-4], Alfredo Taboada[1-4], Chia-Yu Lu[2-4] and Kuo-Jen Chang[3-4]

[1] Univ. Montpellier, UMR 5243, F-34095, Montpellier, France.
[2] Dept. of Geology, National Taiwan University, Taipei, Taiwan.
[3] Dept. of Civil Engineering, National Taipei Univeristy of Technology, Taipei, Taiwan.
[4] International Laboratory (LIA), "ADEPT," CNRS-NSC, France-Taiwan.

Taiwan is a good place to study mountain building during the transition from oceanic to continental subduction. The obliquity of plate convergence involves the progressive subduction of the continental margin of China inducing the fast growth of the mountains. Due to the high convergence rate (~ 9 cm/yr) between Eurasia and Philippine Sea plates (PSP), deformation and erosion rates are extreme (horizontal shortening > 2 cm/yr on seismogenic faults with vertical motions up to 3 cm/yr). Catastrophic erosion involving landslides induced by typhoons and earthquakes, have sculped in a few million years the sharp relief of the island. Looking at the middle term deformation, most of the shortening is accounted for by just a few major faults on the western foreland side of the wedge and along its backside hinterland against the Philippine Sea upper-plate (Fig. 1a); ~4 cm/yr are absorbed across the frontal faults (Simoes & Avouac, 2006), whereas on the backside ~3 cm/yr are absorbed on the onshore Longitudinal Valley faults (Angelier et al., 2000; Shyu, et al., 2006) and ~2 cm/yr offshore within the PSP along the submerged flank of the Coastal Range (Malavieille et al., 2002). On the opposite, little horizontal shortening occurs within the main body of the wedge due to a strong partitioning of deformation. Such a kinematic pattern closely matches the behavior of experimental erosional wedges with décollements (Fig. 1c). It shows that the main mechanisms of growth can be described by frontal accretion in the foreland Foothills and basal accretion of tectonic units at depth under the hinterland. Basal accretion is at the origin of rapid uplift and exhumation of wedge material accounting for most of the vertical component of shortening. Intra-crustal décollements involving flats and ramps localized within the subducting continental margin of Eurasia favor such a style of deformation partitioning and wedge growth. Early décollements are then passively uplifted and folded during continuous underplating processes.

Thus, a direct relationship exists between tectonics (shortening inducing the partitioning between horizontal and vertical displacements on faults) and surface processes contributing to huge material transfer in Taiwan (Fig. 1b). Such a coupling has important consequences : - The main seismogenic faults are located at the boundaries of the wedge both in front (foothills) and along its backpart (in the Longitudinal valley and offshore). - Most of the deformation that is responsible for the growth of the hinterland is taken into account by aseismic ductile strain at depth below the Central Range. Both, the high heat flow and the low sismicity observed beneath the Central Range, are consistent with this behavior at the scale of the orogen.

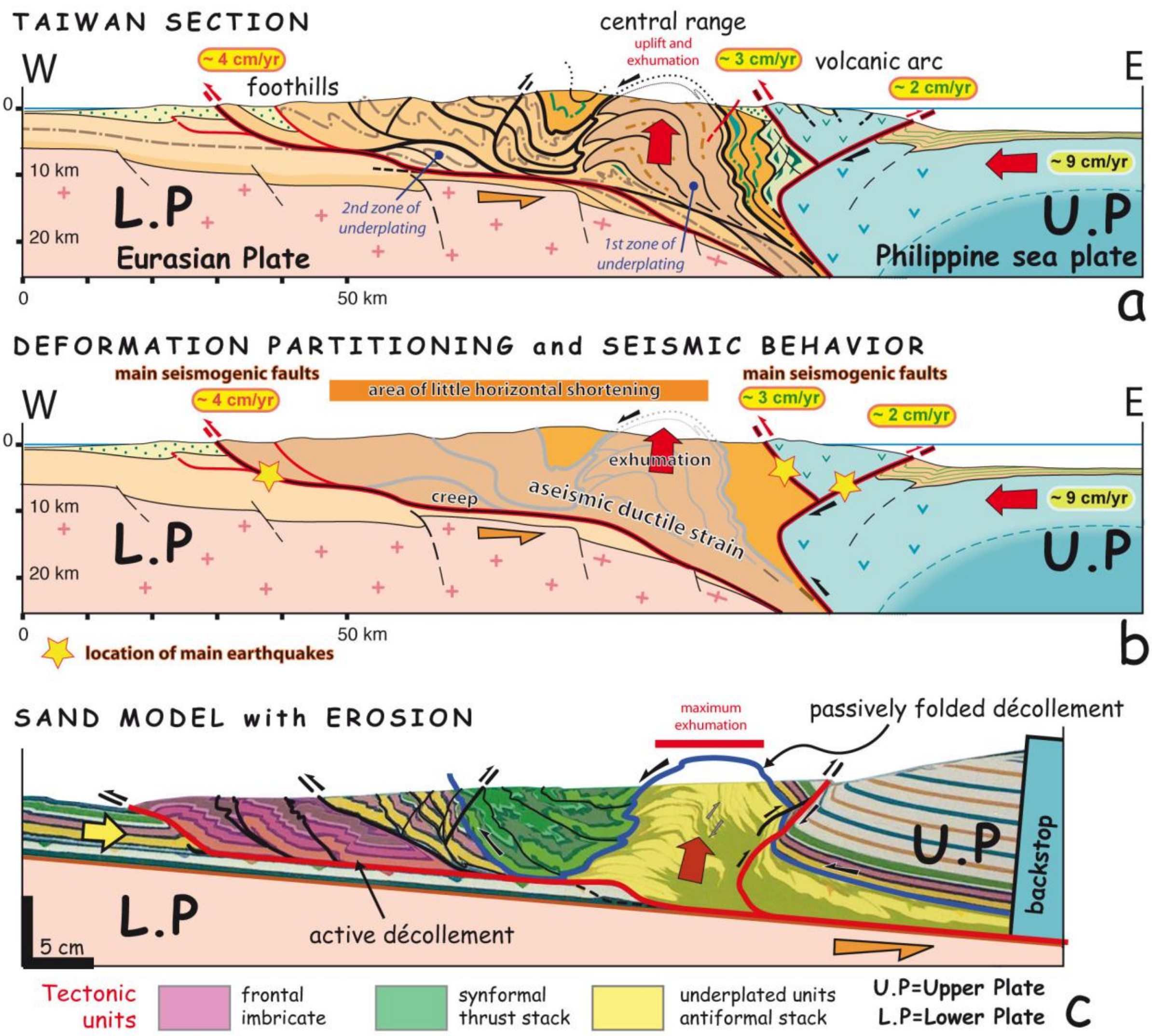


Figure 1: See explanation in the text.

References:

Angelier, J., Chu, H.-T., Lee, J.-C., Hu, J.-C., 2000. Active faulting and earthquake risk: the Chihshang Fault case, Taiwan, J. Geodyn. 29, 151-185.

Malavieille, J., Lallemand, S.E., Dominguez, S., Deschamps, A., Lu, C.-Y., Liu, C.-S., Schnürle, P., and the ACT scientific crew, 2002. Arc-continent collision in Taiwan: New marine observations and tectonic evolution, Geological Society of America Special Paper 358, p. 187–211.

Shyu, J.B.H., Sieh, K., Chen, Y.-G., and Chung, L-H., 2006. Geomorphic analysis of the Central Range fault, the second major active structure of the Longitudinal Valley suture, eastern Taiwan, GSA Bulletin, v. 118; no. 11/12; p. 1447–1462; doi: 10.1130/B25905.1

Simoès, M. & Avouac, J.P., 2006. Investingating the kinematics of mountain building in Taiwan from the spatiotemporal evolution of the foreland basin and western foothills, Journal of Geophysical Research, 111, doi: 10.1029/2005JB004209.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

TEMPORAL AND SPATIAL ORGANISATION OF FAULTING IN FRICTIONAL WEDGES.

Baptiste C.L. Mary[1] , Bertrand Maillot[1] and Yves M. Leroy[2]

[1] Département Géosciences et Environnement, Université de Cergy-Pontoise, France.
[2] Laboratoire de Géologie, CNRS, Ecole Normale Supérieure, Paris, France.

The spatial and temporal organization of thrusting in accretionary wedges and in fold-and-thrust belts results from the coupling between tectonics, erosion and the degradation of the rock strength with the accumulation of deformation. A quantitative assessment of this coupling is presented and based on a simple approach which combines geometrical construction à la Suppe (1983) and optimization techniques which are classical in soil mechanics.

There are fundamental questions still open regarding the mechanics of accretionary wedges and fold-and-thrust belts. One issue is the recurrence time of the activation of out-of-sequence thrusts such as the Chelungpu fault in the foreland of Taiwan (Angelier et al., 2003) or the Splay fault in the Nukano transect of Nankai wedge (Moore et al., 2007). The exhumation of metamorphic rock, observed in the central region of Taiwan, has been reproduced experimentally (Malavieille, 2010) and deserves now some mechanical analyses. The reasons for the anomalous vergence of the fault-related folds such as in Cascadia subduction zone (Gutscher et al. 2001) are still debated. A simple protototype of a triangular wedge resting on a basal layer of uniform thickness in contact with a straight decollement at the base is proposed to shed light on theses issues.

Our understanding of frictional wedges is based on the critical taper theory of Dahlen (1984) and Lehner (1986). Consider a wedge of topographic slope α resting on a decollement dipping at β. The critical taper αc is function of this dip and of the frictional properties of the decollement and of the wedge material. If the topographic slope is less than the critical slope, the deformation occurs at the back of the sub-critical wedge and a forward sequence of folds produces a relief responsible for the increase in the average topographic slope. The deformation is transferred to the front as the slope increases and the whole wedge slips on the decollement for critical slope conditions without further internal deformation. The account of the basal layer below the triangular wedge, as in our prototype, becomes important at this stage since the frontal deformation leads to the accretion of incoming sediments to the wedge. It is shown that the increase in frontal relief because of accretion produces the activation of out-of-sequences which are positioned where the folds developed during the forward sequence. The recurrence time of this activation is function of the distance to the front and also to the thickness of the basal layer. The thicker is the basal layer, the shorter is the recurrence time. The further away is the out-of-sequence thrust from the front, the longer is the recurrence time of its activation.

The introduction of damage along activated thrusts, reflected by a drop in the friction angle of any activated ramp, changes completely this spatial and temporal organization. Accretion still results in the activation of out-of-sequence but there is no periodicity neither in time and space. The thickness of the basal layer still has the same influence on the frequency of activation of the out-of-sequences.

Erosion is accounted for with rules which are those considered for analogue models in the laboratory (Malavieille, 2010). The material in the central region of our prototype above a slope set to the pre-determined value αe is eliminated. This erosion process is not continuous and activated every Δte increment in time. If the erosion is continuous, and αe slightly smaller than αc, a fold with an hinterland ramp is obtained. The vergence is foreland otherwise. Increasing the increment Δte between two erosion steps leads to exhumation within the central region with foreland verging thrusts towards the wedge front. The spacing between these thrusts decreases with increase in the increment Δte.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

STRUCTURAL AND PETROPHYSICAL CHARACTERIZATION OF MIXED DRAIN/BARRIER FAULT ZONES IN CARBONATES: EXAMPLE FROM THE CASTELLAS FAULT (SE FRANCE)

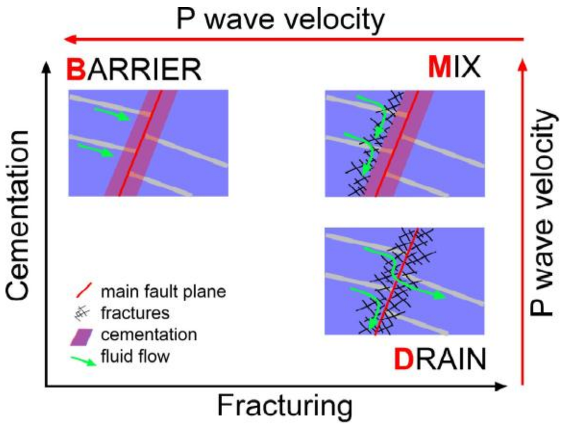
Christophe Matonti[1], Juliette Lamarche[1], Yves Guglielmi[1], Lionel Marié[1]

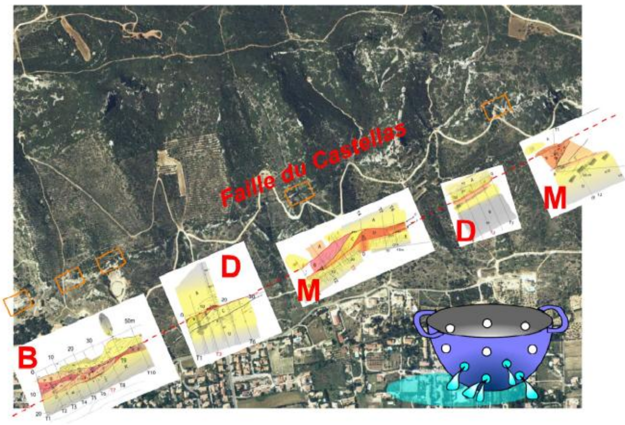
[1] Université de Provence

Fault-zone petrophysical characterization is a crucial issue in reservoir exploitation, because fault zones can behave either as hydraulic barriers or as drains. In the first case, fault zones lead to compartmentalizing of the reservoir; in the second case, they connect porous volumes and drain fluids along high permeability corridors. In addition, combining petrophysical analyses with fault-zone structural characterization is a challenge, because faults may display a number of different hydraulic properties, depending on the presence of an impermeable core, the fault-zone width and complexity, and the diffusivity of the fracture pattern (density, connectivity, and strike).

The Castellas fault zone affects carbonate rocks with a plurimeter scale offset along 1.5 km of outcrop. In order to decipher the structural control on fault petrophysic and hydraulic character, we performed high resolution structural mapping in the field, as well as porosity-VP measurements in the laboratory, along with thin sections analysis of deformations and diagenetic histories. Field structural mapping shows that the fault-zone architecture displays strong lateral variations at the hectometre scale characterized by breccia core thicknesses of 0 to 5 m, one or several slip planes, and varying densities, thicknesses and fracture patterns within the damage zone. The fault zone heterogeneity may be related to several parameters, such as the magnitude of the throw and the position along the fault or the affected rock facies. Laboratory measurements revealed a strong porosity reduction correlated to a P-wave velocity increase, related to the cementation of pore volumes within a decameter area around the fault plane. This fault sealing occurred mainly through a chemical diagenesis related to fluid circulation within laterally variable fault-zone heterogeneities that were inherited from the fault zone architecture.

A conceptual model of the fault zone's current hydraulic properties in 3D is proposed, in which the fault zone acts as a mixed drain/barrier element. Two contrasting fault flow units are defined: (1) sealed impermeable fault tips and (2) more or less permeable units within which flow can occur either perpendicular or parallel to the fault-zone strike. This model could not only represent relatively small faults with moderate offset, but also suggests the complexity such faults can contribute to fluid flow in carbonate reservoirs.


P wave velocity
BARRIER
MIX
Cementation
P wave velocity
main fault plane
fractures
cementation
fluid flow
DRAIN
Fracturing


Faille du Castellas
B
D
M
D
M

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

STRUCTURE AND KINEMATICS OF THE MØRE-TRØNDELAG FAULT COMPLEX, MID NORWAY.

Christophe Pascal[1], Aline Saintot[1,2], Aziz Nasuti[2], Emil Lundberg[3] and Christopher Juhlin[3]

[1] Institute of Geology, Mineralogy & Geophysics, Ruhr University, Bochum, Germany.
[2] NGU, Geological Survey of Norway, 7491 Trondheim, Norway.
[3] Department of Earth Sciences, Uppsala University, Sweden

The Møre-Trøndelag Fault Complex (MTFC) is one of the most prominent fault zones of Norway both onshore and offshore. It strikes ENE-WSW, paralleling the coastline of south central Norway, and separates the northern North Sea basin from the deep Mesozoic Møre and Vøring Basins. Onshore, the MTFC can be traced from the Møre region north-eastwards along the northern margin of the Western Gneiss Region (WGR), and across the Grong–Olden Culmination towards the Børgefjell Basement Window, where it dies out in a horsetail splay. The MTFC formed most probably towards the end of the Caledonian Cycle. Structural mapping in combination with analytical dating techniques have revealed three main phases of activity along the MTFC: (1) Early Devonian sinistral strike-slip characterised by semi-ductile deformation, (2) Early Permian sinistral transtension and (3) Late Jurassic (to Early Cretaceous?) normal dip-slip. Reactivation of the MTFC during Cenozoic times has been proposed but, to date, no evidence for it has been found yet.

Little is known about the deep structure of the MTFC (e.g. dip directions of the faults), the links with the offshore fault segments and the precise kinematics and segmentation of the whole system. The “MTFC integrated” project was designed in order to address these important key-points. Firstly, we used a large panel of geophysical methods (i.e. gravimetry, magnetic profiling, EM and seismic reflection/refraction) constrained by petrophysical sampling and structural field work. Our geophysical observations suggest that major faults reactivate the steeply-dipping ENE-WSW metamorphic foliation. As a consequence, the MTFC onshore appears to bound a major horst structure, similar to the ones imaged by long-range seismic profiling offshore. Furthermore, analysis of regional magnetic and gravity analysis allows for tracing the MTFC as a curved system linking with the major faults of the Møre Basin offshore.

Fault slip analyses were also carried out on more than 200 fault planes in the southern MTFC onshore. MTFC-parallel slickensided planes developed along the ENE-WSW trending metamorphic foliation showing that the foliation was favourably orientated to be the locus of shear and confirming the geophysical findings. Fault kinematics are dominated by dip-slip normal faulting, compatible with a NNW-SSE extensional paleostress field. Interestingly, only one phase of tectonic activity can be recognised in the southern MTFC. In addition, the fault complex is known for exhibiting a great variety of fault rocks. However, our observations show that this applies to some of the primary segments of the northern part of the MTFC onshore. In its southern part, a restricted variety of fault rocks associated with laumontite minerals is found.

Our final conclusions are (1) brittle reactivation of the MTFC occurred almost exclusively along the pre-existing ductile grain, (2) the southernmost faults of the MTFC onshore dip towards the south and (3) they represent the latest propagation and widening of the MTFC which, presumably, occurred in Late Jurassic.

References

Lundberg, E., & Juhlin, C., 2011. High resolution reflection seismic profiling over the Tjellefonna fault in the Møre-Trøndelag Fault Complex, Norway, *Solid Earth*, submitted.

Nasuti, A, Pascal, C., Ebbing, J., and Tønnesen, J.F., 2011a. Geophysical characterisation of two segments of the Møre-Trøndelag Fault Complex, Mid-Norway, *Solid Earth*, 2, 125–134

Nasuti, A, Pascal, C., and Ebbing, J., 2011b. Onshore-offshore potential field analysis of the Møre-Trøndelag Fault Complex and adjacent structures of Mid Norway, *Tectonophysics*, in press.

Saintot, A. & Pascal, C., 2010. A contribution to the kinematics of the Møre-Trøndelag Fault Complex (Western Norway). *EGU 2010*, Vienna.

APPLICATION OF A DAMPED REGIONAL-SCALE STRESS INVERSION METHOD: STRESS FIELD INSIGHT AROUND AND BENEATH THE VATNAJÖKULL GLACIER IN ICELAND

Romain Plateaux[1], Nicole Béthoux[1] and Françoise Bergerat[2]

[1] GeoAzur (UMR 6526), CNRS-UNS-OCA-IRD-UPMC, Observatoire Océanologique de Villefranche, B.P.48, La Darse, 06235 Villefranche-sur-Mer, France
[2] ISTeP (UMR 7193), CNRS-UPMC, boîte 117, 4 place Jussieu, 75252 Paris cedex 05, France.

A dense and sensitive seismic network (South Iceland Lowlands: SIL) covering a large part of the emerged Mid-Atlantic ridge in Iceland gives us the way to study in great detail the state of stress within the crust from focal mechanisms. During the period from 1991 to 2009, some 240 756 earthquakes occurred on land ranging from -2.3 to 6 in magnitude (M_w). Previous studies took benefit for inverting focal mechanisms in Iceland mostly on the two transform zones and on the ridges off-shore (e.g., Bergerat, 1998; Angelier et al, 2004; Plateaux et al, 2010). However, the central part of Iceland remains unexplored in terms of crustal stress: the basement underlied by the Vatnajökull glacier within the East Volcanic Zone. The Vatnajökull region includes four active central volcanoes: Bardarbunga, Grimsvötn, Harmarinn and Kverkfjöll. In this area, the SIL network recorded 5997 earthquakes, each of them associated with a focal mechanism, clustering around active volcanoes.

The purpose of the present work is to establish a first insight of the stress field in such complex region using a damped regional-scale inversion method described by Hardebeck et al, (2006). The usual practice in inversion process consists in dividing the studied area into several subareas and to independently compute the stress tensor from the focal mechanisms of each subarea. Here, a flatness constraint is added between each subarea to remove extreme data which can be partly attributed to artifacts while retaining any stress variations that are strongly required by the data. In order to check the stability of inversion results we performed different tests that are commonly used in geophysical inverse techniques such as seismic tomography. We computed (1) a checkerboard test with synthetic data based on focal mechanisms in Vatnajökull region and (2) introduced a randomly perturbation on strike, dip and rake. These tests revealed stable results. We finally (3) checked some subareas with high misfit in order to detect polyphased events within a subarea.

The first insight shows that stress field tendency is largely deviated around central volcanoes although spatial variability arises with low damping. This first result might imply that magmatic processes have strong influence on tectonic processes.

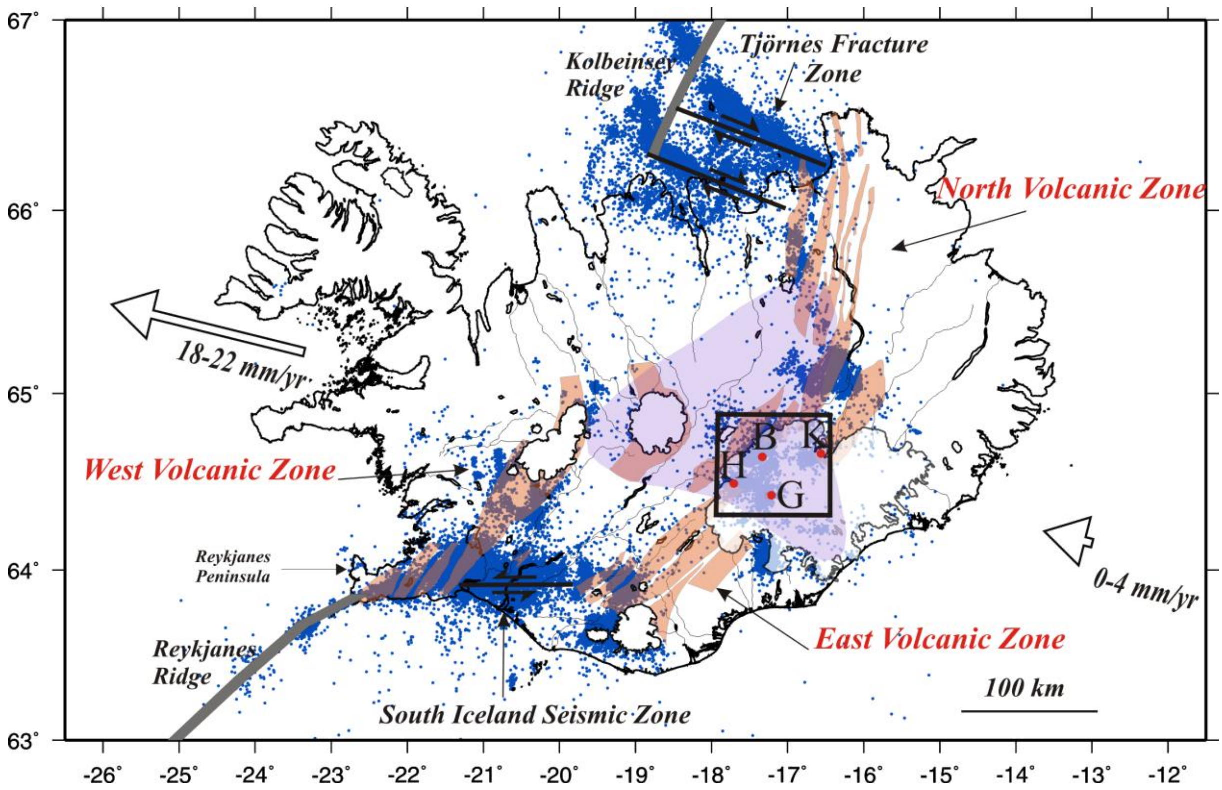


Figure 1 : Location of the studied area and geodynamical context in east Iceland. a) Rift and transform zones in Iceland. Offshore ocean ridge axes of the Mid-Atlantic Ridge as thick grey lines, transform zones as thick black lines with couple of arrows indicating the sense of motion (modified after Angelier and Bergerat, 2002). Main Holocene volcanic systems of onshore rift zones in orange with glaciers left white (after Saemundsson, 1979). Apex zone of the Icelandic hotspot (after Tryggvason et al., 1983) superimposed in light purple. Open arrows show local velocities of Eurasian and North-American plates with respect to the Icelandic hotspot. Blue dots denote earhtquake epicentres from 1991 to 2009 detected by SIL. Abbreviations are central volcanoes as follows : B, Bardabunga, ; G, Grísmvötn ; H, Hamarinn ; K, Kverkfjöll.

Angelier, J.and Bergerat, F. (2002) Behaviour of a rupture of the 21 June 2000 earthquake in South Iceland as revealed in an asphalted car park. Journal of Structural Geology, 24 (12), 1925-1936.

Angelier, J., Slunga, R., Bergerat, F., Stefansson, R., and Homberg, C. (2004) Perturbation of stress and oceanic rift extension across transform faults shown by earthquake focal mechanisms in Iceland. Earth and Planetary Science Letters, 219(3-4), 271-284.

Bergerat, F., Gudmundsson, A., Angelier, J., and Rögnvaldsson, S.Th. (1998) Seismotectonics of the central part of the South Iceland Seismic Zone. Tectonophysics, 298(4), 319-335.

Hardebeck, J. L. and Michael, A. J. (2006) Damped regional-scale stress inversions: Methodology and examples for southern California and the Coalinga aftershock sequence. Journal of Geophysical Research, 111(B11), 1-11.

Plateaux, R., Angelier, J., Bergerat, F., Cappa, F., and Stefánsson, R. (2010) Stress changes induced at neighbouring faults by the June 2000 earthquakes, South Iceland Seismic Zone. Terra Nova, 22(2), 79-86.

Saemundsson, K. (1979) Outline of the geology of Iceland. Jokull 29, 7-28.

Tryggvason, K., Husebeye, E. and Stefanson, R. (1983) Seismic image of the hypothesized Icelandic hot spot. Tectonophysics, 100, 97-118

APPROCHES MECANIQUES ET GEOPHYSIQUES POUR L'ANALYSE DE L'ANISOTROPIE ET DE L'EFFET D'ECHELLE DANS LA CRAIE

Róbert Porjesz[1], Françoise Bergerat[2] and Blaise Souffaché[3]

[1] CGGVeritas, Hampson Russell Software & Services, Crawley, RH10 9QN, Angleterre
[2] ISTeP, UMR 7193 CNRS-UPMC, case 117, 4, place Jussieu, 75252 Paris cedex 05, France.
[3] Sisyphe, UMR 7619 CNRS-UPMC, case 105, 4, place Jussieu, 75252 Paris cedex 05, France.

Depuis l'Antiquité, le sous-sol de Paris a été exploité pour ses divers matériaux : calcaire grossier, craie, argile et gypse. Leur extraction se fit d'abord à ciel ouvert, puis se poursuivit sous terre, d'abord par la méthode des *piliers tournés* puis par celle des *hagues et bourrages,* contribuant à l'affaiblissement des terrains sus-jacents ce qui donna lieu à de nombreux accidents. D'importants efforts furent entamés, dès la création de l'Inspection des Carrières (1777), pour conforter les vides souterrains, cependant, de nos jours, face au rythme de la construction, cette problématique demeure. La complexité du problème de stabilité des roches étant un sujet vaste, ici nous ne considérons que quelques aspects de celui-ci. Les questions que nous nous posons dans ce travail se réfèrent essentiellement à l'analyse de la validité des résultats expérimentaux obtenus en laboratoire et ensuite extrapolés à une échelle plus importante, de l'ordre d'une dizaine de mètres :

- Est-ce que les résultats des essais sur un seul échantillon (indépendamment de l'échelle étudiée) peuvent être considérés comme représentatifs ou faut-il plutôt envisager une approche statistique?
- Peut-on extrapoler les résultats obtenus à partir des essais de laboratoire, portant sur des éprouvettes de taille obligatoirement réduite, à la taille du massif pour déduire les propriétés de ce dernier ?
- Comment tenir compte non seulement des difficultés posées par le transfert d'échelle, mais aussi par la présence des différentes discontinuités (failles, diaclases, etc.) visibles ou cachées à l'intérieur du massif étudié ?

Pour entreprendre ce travail d'analyse mécanique à différentes échelles, des carrières souterraines à accès facile ont été choisies permettant d'une part le prélèvement d'un certain nombre des échantillons et d'autre part des auscultations géophysiques *in situ*. La carrière souterraine Saint-Michel de Bougival, dans la craie, avec des galeries d'environ 5m de large aisément accessibles et des piliers de 5 à 10m de côté permettant des auscultations géophysiques, correspond à ces critères. Pour déterminer les paramètres géomécaniques recherchés différentes mesures ont été effectuées sur les piliers et sur les éprouvettes :

- Les auscultations géophysiques (sismique marteau) à une échelle métrique ont consisté à mesurer les vitesses des ondes primaires et secondaires pour ensuite calculer les modules de Young et coefficients de Poisson dits « dynamiques ». Des piliers avec et sans discontinuités visibles ont été choisis pour pouvoir étudier aussi l'effet de la présence de fractures. Enfin, l'influence du recouvrement (épaisseur variant de 14 à 50 m pour la carrière étudiée) a également été examinée.
- Des éprouvettes de 40mm, 60mm et 100mm de diamètre ont été soumises à des essais en laboratoire. Les essais non-destructifs ont permis d'obtenir la vitesse des ondes ultrasoniques et ainsi de calculer le module de Young dynamique à l'échelle centimétrique. Les essais destructifs (compression simple) ont fourni les module de Young et coefficient de Poisson statiques.

La dispersion importante des paramètres analysés, très probablement induite par l'hétérogénéité de la roche, nous suggère qu'une approche statistique, donc des mesures sur de nombreuses éprouvettes, est la plus appropriée. Si peu d'échantillons sont analysés, il est fort probable que les résultats ne soient pas représentatifs.

Aucun effet d'échelle bien défini des paramètres dynamiques sur la roche saine (sans discontinuités visibles) n'a pu être identifié. Les modules de Young des éprouvettes (de toutes tailles) et ceux des piliers sont du même ordre de grandeur, la différence entre eux semble être inférieure à l'incertitude sur les mesures. Cette même conclusion a été obtenue pour les paramètres statiques, bien évidement uniquement pour les différentes tailles d'éprouvettes.

Les discontinuités contenues dans les piliers, en revanche, semblent influencer notablement les valeurs du module de Young. Une tendance marquée à la diminution en fonction de la « densité » de discontinuités dans la roche a pu être observée.

Finalement, l'analyse de l'effet de recouvrement, ne nous a pas permis d'identifier une tendance bien définie. L'incertitude sur les mesures, probablement dues aux imprécisions des mesures elles-mêmes et à l'hétérogénéité de la roche, semble être plus importante que l'effet de charge sur les piliers.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

CATACLASTIC ANALYSIS METHOD OF DISCONTINUE DISPLACEMENTS AND RESULTS OF TECTONOPHYSICAL ANALYSIS OF DISTRIBUTION OF STRESS MAGNITUDES IN THE SOURCES OF CATASTROPHIC EARTHQUAKES

Yuri Rebetsky[1]

[1] Institute of Physics of the Earth RAS, Moscow, Russia

The method of cataclastic analysis of discontinuity dislocation (MCA) incorporated the main principles for calculation of stress parameters and irreversible deformations, which follows from plasticity theory. This method consisting from four stages of reconstruction, consequently assesses components of complete stress tensor and normalized tensor of seismotectonic strain increment. The method is based on energetic principles of plasticity theory, which is used to assess stress tensor components, maximizing dissipation of internal elastic energy of seismotectonic strain tensor. This requires simultaneous calculations of stress tensor and irreversible strains, which is missing in all above-mentioned methods.

Possibility to assess not only orientation of principal stress axis but also stress magnitudes in this method is based on earthquake source mechanisms plus seismological data on stress-drop, geophysical data on topography and earth crust density together with general principles of geomechanics and theory of brittle failure. Methodologically closest to the MCA is the method discussed in [J. Angelier, J. Struct. Geol., Vol. 11, N ½, 1989,], which uses geological data on striation angles.

Application of the MCA method for stress reconstruction in regions of catastrophic earthquakes make it possible to watch peculiarities tectonic stress distribution before strong earthquake for the first time. Thus, for Sumatra-Andaman earthquake in 2004 (M_w=9.3) it was found that the region responsible for rupture nucleation was located in the zone of maximum stress gradient. To north was located large (400 – 500 km long) low intensity of effective confining pressure p^* (tectonic pressure after subtraction of fluid pressure) and to the south was 300 – 400 km long area of maximal intensity of effective pressure. Such stress distribution analysis geomechanics from point of view shows that in regions characterized by high level of effective confining pressure brittle failure developed by spending essential part of internal energy of elastic strain to overpass frictional forces over rupture (this energy finally transformed in heating). While in regions of low intensity of effective confining pressure brittle failure is developed most effectively. It is found that strong earthquakes occur in regions of moderate to low level of effective pressure, in which, according to Coulomb theory, maximal shear stresses are low. This regularity makes it possible to formulate criteria for detection of zones capable to generate anomalously large earthquakes in seismoactive regions of earth crust.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

CONTROL OF NORMAL FAULT GROWTH AND ARCHITECTURE BY SUB-HORIZONTAL FAULTS

Vincent Roche[1, 2], Catherine Homberg[1], Muriel Rocher[2],

1. UPMC, ISTEP, UMR 7072, case 129, 4 place Jussieu, 75252 Paris Cedex 05, France, vincent.roche@upmc.fr.
2. IRSN (Institute for radiological protection and nuclear safety), DSU/SSIAD/BERIS, B.P.17, F-92262 Fontenay-aux-Roses Cedex.

The Callovian-Oxfordian clay formation is currently studied by Andra in Eastern Paris basin (France) for hosting a deep geological disposal of radioactive waste. This 500 m-deep clay formation is surrounded by two limestone formations. In such a “multilayer system”, faults within limestones sometimes propagate to clay layers. Such a situation could decrease the containment ability of the clay formation by creating preferential pathways for radioactive solute towards limestones. IRSN is conducting studies in support of the regulatory review of this disposal project. In order to improve our understanding of fault development in such alternations of more or less competent rocks, well-exposed meso-scale faults systems cutting clay-limestone alternations have been investigated in the South-Eastern basin, France. Based on a selected data set among the observed normal faults with centimetre to decimetre offsets, we illustrate here the important role of sub-horizontal faults located in clays on both the propagation and the architecture of the normal faults. In the three selected sites, showing normal faults crossing decimetre to metre-thick clay-limestone alternations, sub-horizontal faults are observed within some of the clay layers, both close to and at a distance from the normal faults. They are referred below as CHF (clay horizontal faults). Careful examinations of the CHF planes reveal that, in each site, the slip vector has direction similar to the calculated minimum principal stress responsible for the normal faults, and thus confirms a genetic link between the CHF and the meso-scale normal faults.

Faults restricted by CHF were observed in two sites (Figure). Their maximum displacement varies between 1 and 12 cm in the first one and between 4 and 43 cm in the second one. The restriction by CHF induces changes in the displacement profiles, a typical flat-topped pattern with a low gradient zone near the nucleation point and large but various gradients at tips. Such changes in the displacement profiles are similar to those observed along faults restricted by lithological interfaces, whatever the restriction process. The fault architecture is also strongly modified as the displacement accumulates on the restricted faults: the number of fault segments increases with the maximum displacement, causing the fault thickness to expand, up to 2m close to the restrictor, especially within limestones. Although no fault crossing the CHF has been observed in these two sites, we speculate that restriction occurs till a maximum displacement threshold as it does for faults restricted by lithological interfaces.

In the third site, showing several outcrops, we observe normal fault zones passing through CHF. They consist of one or more thin sub-vertical segments in limestones. In the clay layers affected by CHF, fault segments may propagate across CHF or may connect to it. We first show that the thickness of the fault zones depends on the presence of CHF in surrounding clays and could become very large relatively to the fault displacement, up to about 2 m for a fault with ~ 20 cm maximum displacement. Secondly, where fault segments, located in the two limestone units surrounding a clay layer, abut again the CHF in the clay, they may define a connected overstep zone of compressive type with a very large width, which seems to increase with the thickness of the clay unit. This pattern implies therefore an increase of the fault length in clays. Thirdly, study of the displacement profiles show that the displacement gradients are constant in clay layers whenever CHF are present or not, with a mean value greater than in limestones. Thus, even if CHF guide the fault path, the important fault length in clays contributes to discourage the vertical propagation of the normal fault.

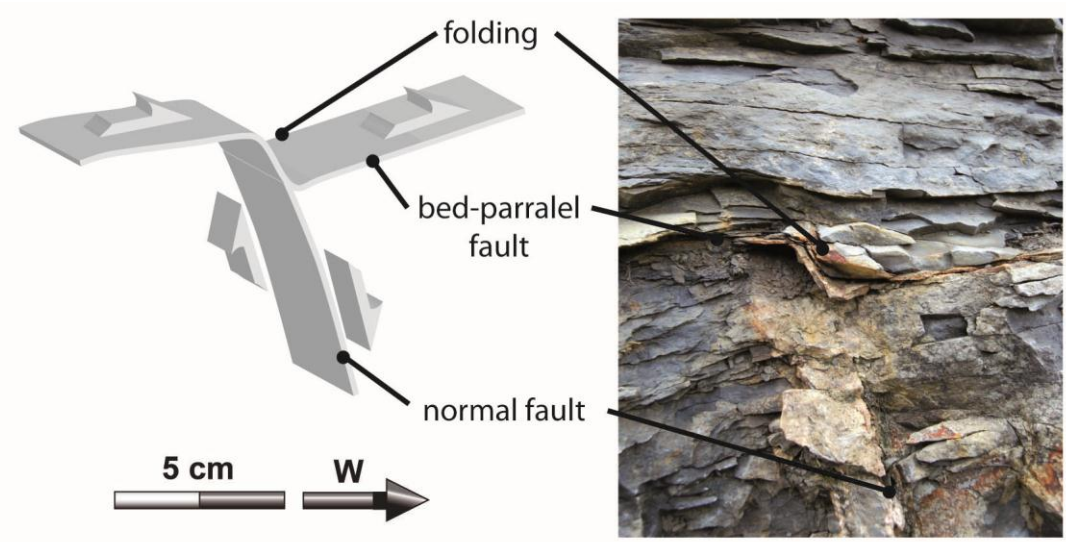


Figure. Normal fault restricted by a bed-parallel fault within shale in the South-Eastern basin, France.

PLEISTOCENE ALLUVIAL DEPOSITS DATING ALONG FRONTAL THRUST OF CHANGHUA FAULT IN WESTERN TAIWAN: THE COSMIC RAY EXPOSURE POINT OF VIEW

Lionel L. Siame[1,7], Rou-Fei Chen[2,3,7], Florence Derrieux[1], Jian-Cheng Lee[2,7], Kuo-Jen Chang[4,7], Didier L. Bourlès[1,7], Régis Braucher[1,7], Laetitia Léanni[1], Chu-Chun Kang[5], Chung-Pai Chang[5,7], Hao-Tsu Chu[6,7]

[1] Centre Européen de Recherche et d'Enseignement en Géosciences de l'Environnement, U.M.R. 6635 CNRS-INSU, Université Aix Marseille, B.P.80, Plateau de l'Arbois, 13545, Aix-en-Provence cedex 4, France.
[2] Institute of Earth Sciences, Academia Sinica, 128 Academia Road Sec. 2, Nankang, Taipei 115, Taiwan.
[3] Department of Geology, Chinese Culture University, 55, Hwa-Kang Road, Yang-Ming-Shan, Taipei , Taiwan.
[4] Department of Civil Engineering, National Taipei University of Technology, Taipei, 106, Taiwan.
[5] Center for Space and Remote Sensing Research, National Central University, 300, Jhongda Rd., Jhongli, Taoyuan, Taiwan.
[6] Central Geological Survey, Ministry of Economic Affairs, P.O.BOX 968, Taipei, Taiwan.
[7] LIA (Associated International Laboratory) ADEPT (Active deformation and Environment Programme for Taiwan), France (CNRS/INSU) and Taiwan (NSC)

To tackle the history of active thrusts, it is necessary to open the observation window on time scales on the order of 10^4-10^5 years by studying the surface morphologies resulting from their activities. Because fluvial systems are particularly sensitive to recent environmental changes, geomorphic features such as alluvial terraces are frequently used as markers to gauge tectonic deformation. Together with the measurement of cumulative displacements, the chronological framework of emplacement and abandonment of these geomorphic markers is thus fundamental to determine long-term fault slip-rates. In Taiwan, the geomorphic features associated to fault activity have been detailed studied with a high level of resolution; however, the use of deformed and partially-preserved alluvial terraces is often hampered by the absence of well-documented ages. The purpose of this paper is two-fold. In this poster, we present how the cosmogenic dating method (*in situ*-produced ^{10}Be) can be used to constraint the chronological framework of alluvial deposits over a Pleistocene time scale. In this study, we used the modeling of the down-depth exponential decrease of cosmogenic concentration in the rocks and soils exposed to cosmic rays (*e.g.*, Siame et al., 2004; Braucher et al., 2009). Thanks to a comparison of our cosmogenic-derived ages with existing data, we present a regional chronological framework for the Pakua-Tadu area along the Changhua Fault, one of the most active frontal thrusts in the Western Foothills of the Taiwan mountain belt, and discuss its tectonic implications for the timing of propagation of the deformation front during the last 500 kyr.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

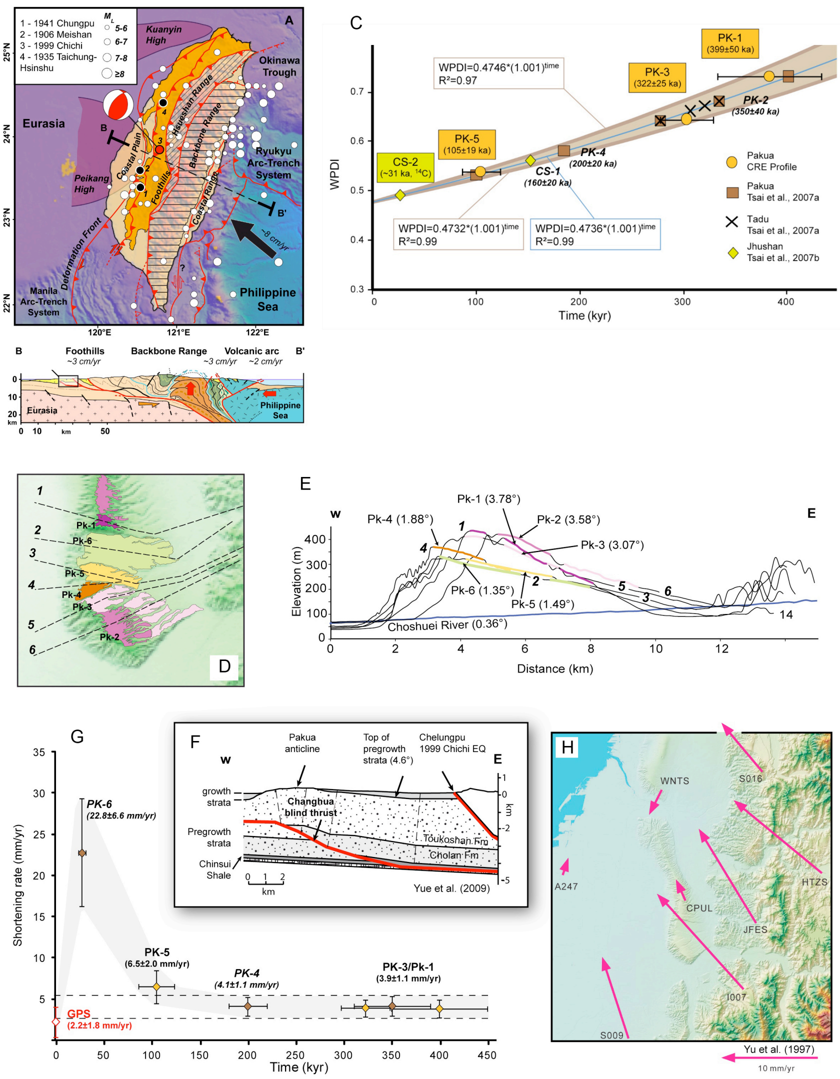


Figure - A. Tectonic framework and main structural units of the Taiwan collision zone (after Angelier et al., 2009). Large arrow indicates the plate convergence direction of Philippine Sea plate relative to Eurasia (Sella et al., 2002). Open circles locates earthquakes with ML≥5 (1900-2006; Central Weather Bureau of Taiwan). Solid circles locate Western Foothills' largest destructive earthquakes. Focal mechanism of the Chi-Chi mainshock after Chang et al. (2000). B. Section across the orogen showing the main zones of active faulting and exhumation (after Malavielle, 2010). Numbers refer to short-term shortening estimates through the deformation front (Simoes and Avouac, 2006), the Longitudinal Valley (Angelier et al., 2000; Shyu, et al., 2006) and offshore within the Philippine Sea plate (Malavieille et al., 2002). C. Regional terrace correlation using the cosmic ray exposure ages for the depth profiles sampled within Pk-5, Pk-3 and Pk-1 alluvial deposits combined with the weighted profile development indices (WPDI) determined by (Tsai et al. 2007b). The terrace CS-2, radiocarbon-dated by Ota et al. (2002), is also integrated in the regression. The thin blue line corresponds to the regression relationship using the average age values. Thick brown lines correspond to the regression relationships obtained using minimum and maximum age values (model uncertainties). Numbers in italic refer to the terrace ages determined using the correlation between WPDI and time. D. Close-up on the southern termination of the Pakua Tableland locating the topographic profiles shown in E. Topographic profiles showing the terrace dip values (determined over their best preserved sections) and the present-day gradient of the Choshuei River. F. Simplified structural interpretation of the Pakua Anticline (after Yue et al., 2009). Toukoshan-Cholan and Chinsui formations are Pleistocene and Pliocene, respectively. G. Horizontal shortening rates associated to the Changhua Fault derived from the terrace dip values. H. Schematic map of the GPS vectors for the stations located in the vicinity of the Pakua Tableland (after Yu et al., 1997).

References

Angelier, J., Chu, H.T., Lee, J.C., and Hu, J.C., 2000. Active faulting and earthquake risk: the Chihshang Fault case, Taiwan. Journal of Geodynamics, 29, 151-185.

Angelier, J., T.Y. Chang, J-C. Hu, C.P. Chang, L. Siame, J.C. Lee, B. Deffontaines, H.T. Chu, C.Y. Lu, 2009. Does extrusion occurs at both tips of the Taiwan collision belt ? Insights from active deformation studies in the Ilan Plain and Pingtung Plain regions. Tectonophysics, 466, 356-376.

Braucher, R., Del Castillo, P., Siame, L., Hidy, A.J., and Bourlès, D.L., 2009. Determination of both exposure time and denudation rate from an in situ-produced 10Be depth profile: a mathematical proof of uniqueness. Model sensitivity and applications to natural cases. Quaternary Geochronology 4, 56-67.

Chang, H.-S., Wu, Y.-M., Shin, T.-C., Wang, C.-Y., 2000. Relocation of the 1999 Chi-Chi Earthquake in Taiwan. Terrestrial, Atmospheric and Ocean Sciences, 11 (3), 581-590.

Malavieille, J., 2010. Impact of erosion, sedimentation and structural heritage on the structure and kinematics of orogenic wedges : analog models and case studies. Geological Society of America, account GSA Today, v. 20, no. 1, 4-10.

Malavieille, J., Lallemand, S.E., Dominguez, S., Deschamps, A., Lu, C.-Y., Liu, C.-S., Schnürle, P., and the ACT scientific crew, 2002, Arc-continent collision in Taiwan: New marine observations and tectonic evolution, in Byrne, T.B., and Liu., C.-S., eds., Geology and Geophysics of an Arc-Continent Collision, Taiwan: Geological Society of America Special Paper 358, p. 187–211.

Ota, Shyu, B.H., Chen, Y.G., Hsieh, M.L., 2002. Deformation and age of fluvial terraces south of the Choushui River, central Taiwan, and their tectonic implications, Western Pacific Earth Sciences, 2, 251–260.

Sella, G.F., T.H. Dixon, and A. Mao, REVEL: A model for recent plate velocities from space geodesy, J. Geophys. Res., 107, B4, doi:10.1029/2000JB000033, 2002.

Shyu, J.B.H., Sieh, K., Chen, Y.-G., and Chung, L.-H., 2006, Geomorphic analysis of the Central Range fault, the second major active structure of the Longitudinal Valley suture, eastern Taiwan: Geological Society of America Bulletin, 118, 1447–1462.

Siame, L., Bellier, O., Braucher, R., Sebrier, M., Cushing, M., Bourlès, D., Hamelin, B., Baroux, E., de Voogd, B., Raisbeck, G. and Yiou, F., 2004. Local erosion rates versus active tectonics: cosmic ray exposure modelling in Provence (south-east France). Earth and Planetary Science Letters, 220, 345-364.

Simoes, M., and Avouac, J.P., 2006, Investigating the kinematics of mountain building in Taiwan from the spatiotemporal evolution of the foreland basin and western foothills: Journal of Geophysical Research, v. 111, B10401.

Tsai, H., Hseu, Z.Y., Huang, W.S., and Chen, Z.S., 2007a. Pedogenic approach to resolving the geomorphic evolution of the Pakua river terraces in central Taiwan. Geomorphology 83, 14-28.

Tsai, H., Huang, W.-S., and Hseu, Z.-Y., 2007b. Pedogenic correlation of lateritic river terraces in central Taiwan. Geomorphology 88, 201–213.

Yu, S.B., Chen, H.Y., and Kuo, L.C., 1997. Velocity field of GPS stations in the Taiwan area. Tectonophysics, 274, 41–59.

Yue, L.F., Suppe, J., and Hung, J.H., 2009. Two contrasting kinematics styles of active folding above thrust ramps, western Taiwan, in K. McKlay, J. Shaw, and J. Suppe, eds., Thrust fault-related folding. American Association of Petroleum Geologists Memoir, 94, 1-34.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

RUPTURE ENVELOPE FOR FAULT SYSTEM REACTIVATION

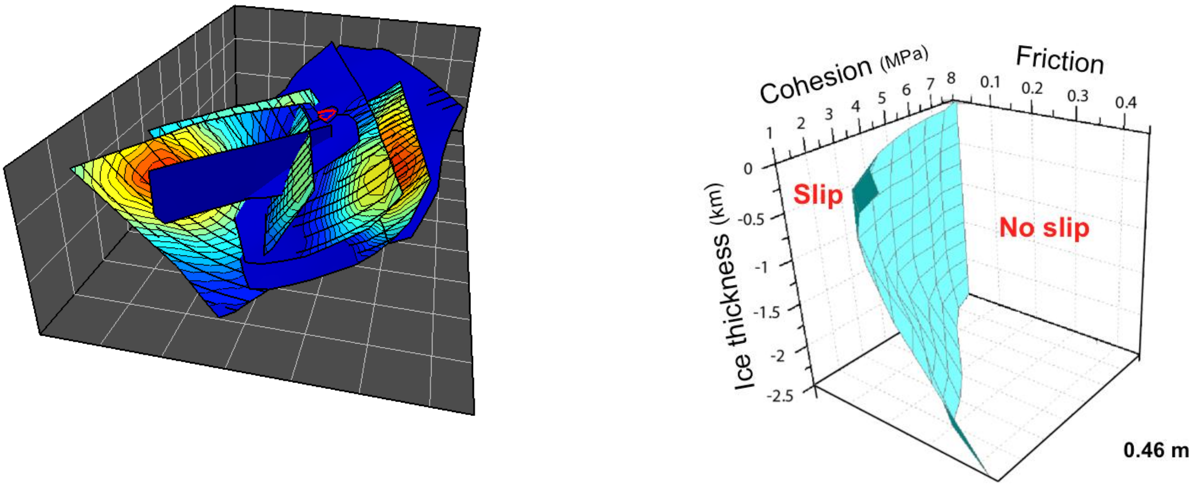
Roger Soliva[1] and Frantz Maerten[2]

[1] Géosciences Montpellier, CNRS, Université Montpellier 2
[2] Schlumberger Montpellier Technical Center (MpTC), Grabels, France

In the last decades of the past century, significant advances on the analysis of fault slip have shown that several main processes are worth to consider to understand the displacement distribution on the surfaces of a fault system. These processes, which can be classified into two categories, « off » and « on fault » processes, comprise the stress orientations and magnitudes, fault segment interaction and linkage, the material properties and heterogeneities (e.g. layering), the 3-D shape of the fault surfaces, and their friction law. These parameters can affect the slip distribution of a fault surface but also the scaling laws and the geometrical attributes of an entire fault system.

It is therefore clear that the sensitivity of a fault system to slip is dependent on all these key parameters and their interplay when stresses are applied. To analyze the interaction of these parameters, we use Poly3D, a boundary element model based on linear elasticity,which accounts for all the processes presented above and demonstrated by field studies. Weusea wide number of simulations to analyze the interplay the multiple variables.This parametric analysis includes variables as the stress orientation, stress gradients at depth, fault friction, cohesion and also the fault system shape. The results are presented and analyzed as 3-D diagrams containing rupture envelopes as a function of these parameters. We apply this methodology to prevent fault slip at the Olkiluotto nuclear waste repository site, where the fault shape and the in situ stresses are well known. The results show that rupture envelopes can be complex in shape as a function of the variable considered in the study. It appears that the stress orientation or stress permutation as for example possible if the stress profiles crosses at depth, are the prominent factors affecting the shape of the reactivation rupture envelope.

a b



Fault system reactivation at the Olkiluotto repository site. (a) Example of numerical simulation of fault slip on the fault system. The box is 1km wide, the colors show the magnitude of slip, and the streamlines are the slickenlines. (b) Example of a curved rupture envelope as a function of friction, cohesion and the stress system applied as the ice thickness above the fault system.

INTERPRETATION OF SALIENT SHAPE FROM PALEOSTRESS FIELDS: EXAMPLES OF CASTELLANE, NICE (FRANCE) AND NORTH TAIWAN SALIENTS

Sonnette Lionel[1,2]

[1] University of Nice Sophia Antipolis (UMR6526), Observatoire de la Côte d'Azur, Géoazur, Villefranche-sur-Mer, France.
[2] LIA-Active Deformation and Environment Program for Taiwan (LIA536 CNRS/NSC).

Numerous foreland mountain belts present an arcuate shape as the Nice and Castellane subalpine chains and the North Taiwan belt which exposed sub N-S and E-O branches. Such curved geological features, also called salient, raise the following questions. Is the curvature inherited or acquired during or after the genesis of the studied salient? How is the paleostress field responsible for the curvature? According to the timing of the curvature acquisition, geological interpretation would be different in terms of structures orientation, especially about the signification of the paleostress fields.

Paleomagnetic investigations have been led in these different salients in order to determine the timing and the amount of vertical-axis rotations which were unknown or badly constrained. Paleostress fields have been interpolated from paleostress directions determined in previous studies. The main results of my study for the Castellane (1), Nice (2) and North-Taiwan (3) salients are the followings:

(1) Interpretation of the paleostress fields of Castellane salient are in good agreement with the rotations and the finite deformation field. The acquisition of the curvature is synchronous to the setting up of the arc.

(2) Paleomagnetic rotations into the Nice salient cannot be interpreted. The deflections of the paleostress lines suggest minor rotations. In contrast, the conservation of the homogeneity of the Oligocene paleostress field between the Castellane and Nice salients implies an important clockwise rotation of the whole Nice salient.

(3) For North Taiwan paleostress events are determined in each branch of the salient but do not fit with the indenter model. I propose an innovative interpretation involving two successive rotation events with a first 60° anticlockwise rotation of the whole salient followed by a progressive clockwise rotation from 15 for the south branch to 30° for the north branch.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

GEODYNAMICS OF THE ALI SABIEH BLOCK (AFAR TRIPLE JUNCTION): NEW INSIGHTS FROM PALEOSTRESS ANALYSIS

Sue Christian (1), Le Gall Bernard (2), Ahmed Daoud Mohamed (2), Rolet Joel (2)

(1) Franche Comté University, UMR 6249, 16, route de Gray, 25000 Besançon, France
(2) IUEM Brest University UMR6538, Place Copernic, 29280 Plouzané, France

Key-words: Afar Triple junction; Ali Sabieh block; brittle deformation; paleostress field; extension; doming; deep geodynamic processes

Tectonics of triple junction zones, of either continental or oceanic type, often lead to complex strain/stress patterns, generally caused by changes in the relative trajectories of the plates involved in the system. The corresponding far stress/strain fields may also interact with more local fields of either tectonic or magmatic origin. Such a geodynamic configuration occurs in the Afar Depression, Horn of Africa, where three recent (<3 Ma) rift axes converge and disrupt the eastern edge of the earlier (30 Ma-old) Afar plume-induced volcanic province. The Ali Sabieh block (ASB) is located on the southeastern edge of the Afar morphologic depression (border between Djibouti Republic and Somalia) [Arthaud et al., 1980]. It exhibits a paradoxal 30 km-large anticlinorium-like structure in a regional extensional tectonic context. Indeed, Jurassic limestones and Cretaceous sandstones outcrop in the core of the structure, surrounded by Neogene volcanics (basalts and rhyolites), which get younger outward of the structure. Moreover, the ASB corresponds to a structural high, with a mean altitude in the range of 500-800m *vs.* 50 m for the surrounding plains.

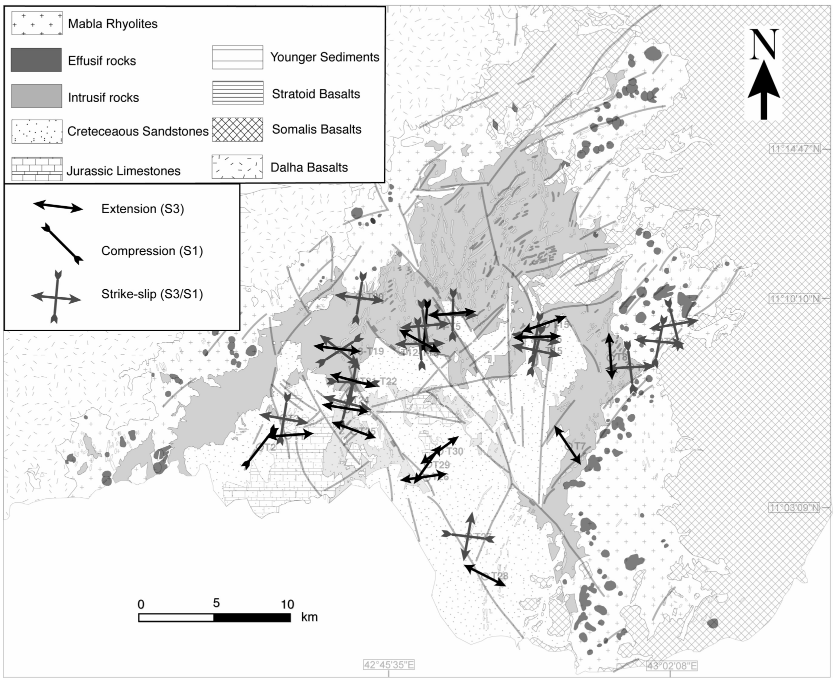
Methods. We provide here new fault/stria data, which allow to better constrain the tectonic evolution of the ASB, and its large-scale structure. We performed a systematic analysis of faulting in the ASB, based on microtectonic measurements and paleostress tensor inversions (600 measures, 31 tensors). The directions of the three principal strain/stress axes (s1> s2> s3) were calculated using the geometrical right dihedra solution (DD), the pressure-tension method (PBT), and the direct inversion method (DI). In a first step (DD), compressive and distensive dihedra are calculated for each site, which give the possible 3D configuration of the tensor [*Angelier and Goguel*, 1979; *Angelier and Mechler*, 1977]. For the second method (PBT), the best-fit theta angle (frictional angle) for each tensor is determined. Thus, P- B- and T-axes are calculated with this optimum theta angle for each fault plane, the final axes for the data set being the barycenter of the P, B, and T distributions. Finally, paleostress tensors have also been calculated for each site by the direct inversion method (DI) based on the minimization of the differential angles between the measured and the computed striae [*Angelier*, 1990]. These last methods allow to establish the shape ratios of the stress/strain ellipsoids ϕ=[(s2-s3)/(s1-s3)].

Data analysis. This approach allowed to precisely map the stress field associated to the brittle deformation of the study area (Figure 1), and partly to constrain the timing of the tectonic evolution, the volcanic rocks being dated. Paleostress fields inferred from brittle deformation are made of two majors signals: normal and strike-slip faulting. The relative chronology has been determined in 3 polyphased sites, showing a first signal in extension, then a second signal in strike-slip. The first phase of extension corresponds to ENE-WSW to WNW-ESE oriented s3 axes and subvertical s1 axes. We point out a regionally stable E-W oriented extension. The second phase is associated to E-W to ENE-WSW s3 axes and N-S to NNW-SSE s1 axes. Both extensional and strike-slip fields are well constrained, with 15 and 14 tensors respectively, distributed all over the ASB, and a good internal homogeneity.

Discussion. The stress distribution shows that these two stress fields are compatible, the s3 axes being stable (globally E-W). Thus, the ASB may have evolved continuously from extensional to transcurrent tectonism, and/or local/regional stress permutation may have occurred between s1 and s2 stress axes, leading to tectonic permutation between extension and strike-slip. Indeed, the very stable E-W direction of extension shows that the ASB's tectonics have been ruled under quite stable extensional conditions from the Neogene onwards. Neither in the field nor on structural maps of the area or satellite images, large normal faults as candidate for a 30 km-wide horst could be determined. On the contrary, we observed some folds at the periphery of the ASB, which could be associated to the 2 reverse paleostress tensors we computed. In this framework, we propose that the ASB evolved as a magmatic dome rather than a horst or an anticline. The doming origin of the ASB is supported both by the internal organization of the structure, and by our detailed paleostress fields. The associated geodynamic context could imply deep processes such as mantle upwelling.

References

Angelier, J., and J. Goguel (1979), CRAS Series, 288, 307-310.
Angelier, J., and P. Mechler (1977), BSGF, 7, 1309-1318.
Angelier, J., (1990) Geophys. J. Int., 103, 363 – 376,.
Arthaud, F, Choukroune, P., Robineau, B (1980), Bull. Soc. Geol. France, 6, 901-908.



Paleostrain/stress maps of the ASB, calculated by Direct Inversion method (INV). Arrows show the projection on the map of the computed azimuth σ3 axis for the extensional (black) and strike-slip (grey) paleostress fields. Bars show the projection on the map of the computed azimuth σ1 axis for the reverse (black) and strike-slip (grey) paleostress fields.

Les Failles : Pourquoi ? Où ? Comment ?
Colloque en hommage à Jacques Angelier, Paris, 17 Novembre 2011
Volume de résumés
****

APPORTS DE LA PHOTOGRAMMETRIE A L'ETUDE DES CHAMPS DE FRACTURES ACTIFS EN ISLANDE.

Thierry Villemin[1], Lionel Sonnette[2], Romain Plateaux[2] et Françoise Bergerat[3]

[1] EDYTEM (UMR 5204), CNRS-Université de Savoie, Campus scientifique, 73376 Le Bourget du lac cedex, France
[2] GeoAzur (UMR 6526), CNRS-UNS-OCA-IRD-UPMC, Observatoire Océanologique de Villefranche, B.P.48, La Darse, 06235 Villefranche-sur-Mer, France,
[3] ISTeP (UMR 7193), CNRS-UPMC, boîte 117, 4 place Jussieu, 75252 Paris cedex 05, France

La déformation cassante se manifeste dans la croûte supérieure par le développement de réseaux de fractures plus ou moins complexes. Ce processus est difficile à suivre in situ et seuls quelques endroits du globe en permettent une étude à la fois qualitative et quantitative. Le rift islandais, à l'instar de quelques autres zones de rift actif comme celle des Afars, est un de ces endroits favorables à la cartographie détaillée de champs de fractures. D'un point de vue géodynamique, le rift islandais est situé sur une frontière entre deux plaques tectoniques divergeant l'une de l'autre à une vitesse relative de 2 cm/an. Il en résulte le développement de toute une série de champs de fractures disposés en relai le long de la frontière de plaque. Ces champs de fractures sont constitués, dans des proportions variables, de fissures ouvertes et de failles normales. L'ouverture des fissures varie entre quelques centimètres et quelques mètres. Les failles actives, dans les terrains holocènes récents où elles s'expriment le plus fréquemment, ont des rejets compris entre quelques dizaines de centimètres et quelques dizaines de mètres. Ces structures sont particulièrement bien visibles en surface du fait de l'absence ou de la faible végétation. Elles sont régulièrement « effacées » par les coulées volcaniques qui viennent rajeunir fréquemment la surface avant d'être elles-mêmes à leur tour fracturées.

Pour étudier ces champs de fractures, l'utilisation de photographies aériennes est parfaitement adaptée, dans la mesure où le terrain, difficilement accessible, ne permet pas une étude classique exhaustive au sol. La résolution des clichés disponibles, réalisés à des échelles variant entre 1/10 000 et 1/30 000, permet de détecter des accidents sub-métriques. Une exploitation photogrammétrique des images ouvre la voie à la mesure des décalages verticaux le long des failles. Pour permettre ces mesures, quelques points connus en coordonnées 3D suffisent. Le terrain, fait de nombreux affleurements rocheux aux détails facilement repérables, offre la possibilité de déterminer directement, par des techniques GPS, les coordonnées d'un grand nombre de points caractéristiques. Ces informations permettent de remonter aux caractéristiques d'orientation externe des images et d'utiliser ensuite les techniques de restitution 3D classiques de stéréo-photogrammétrie.

Trois champs de fractures ont fait l'objet d'études détaillées :

- **Le champ de fracture de Krafla**, situé au sein de la zone Volcanique Nord, a été fortement modifié lors du dernier épisode volcano-tectonique de 1975-1984. Il s'agit d'un champ de fractures de 80 km de long, sur une largeur d'environ 10 km. Une investigation détaillée au niveau de Gjástykki a montré qu'entre 1960 et 1990 il y avait eu à la fois allongement des fractures existantes et apparition de plus d'un millier de fractures nouvelles, la longueur cumulée de l'ensemble des structures passant de 228 km et 312 km.
- **Le champ de fracture de Thingvellir** constitue le principal champ de fractures de la zone volcanique Ouest. Il est essentiellement constitué par des failles normales qui peuvent se suivre depuis des terrains pléistocènes jusqu'à des terrains holocènes de moins de 9000 ans. Les rejets comparés entre Pléistocène et Holocène montrent que l'activité extensive a fortement diminué depuis 100 000 ans. Actuellement, comme le montrent par ailleurs les données de la géodésie satellitaire, la zone volcanique ouest absorbe moins de 10% de la divergence totale.
- **Le champ de fracture de Vogar** est situé sur la péninsule de Reykjanes, à l'extrême sud-ouest de l'île. Ce secteur fait partie d'un ensemble de cinq champs de fractures en échelon, liant d'une part la ride de Reykjanes en mer, à la zone sismique sud-islandaise et à la zone volcanique ouest d'autre part. Une cartographie détaillée des failles a été réalisée sur un secteur d'environ 30 km^2. Des profils d'évolution du rejet des failles ont été réalisés le long des accidents principaux. Ces profils révèlent d'importantes variations du décalage vertical qui résultent de la connexion, par leurs extrémités de plusieurs failles sub-alignées. Différents stades d'évolution sont observés suggérant un processus de croissance en deux étapes, après connexion : lors d'une première étape le rejet augmente au centre de chaque segment mais reste faible au niveau des jonctions entre segments assemblés. S'ensuit une deuxième étape au cours de laquelle les défauts de rejets au niveau des points de connexion seront progressivement comblés.