[PS]Direct Paleo-Overpressure Estimate, from Demonstration to Practical Application: The Sheep Mountain Anticline Example*

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Abstract

Geomechanical concepts and models play an increasing role in geoscience workflows, from exploration to reservoir management. This implies that new equations and parameters govern our earth models. Such models therefore request new data to be controlled. When it comes to mechanics in particular, it is crucial to rely on observations that control paleostress magnitudes. In this presentation, we demonstrate how paleo-stress and paleo-pressures can be estimated in practice from the analysis of calcite twinning. This discussion is based on the study of an outcrop dataset, including structural and geochemical data to validate the proposed approach.

The studied outcrop is Sheep Mountain, an asymmetric basement cored anticline corresponding to a typical Laramide arch of the Bighorn Basin (Wyoming, USA). We show how paleo-principal stress magnitudes during the development of this fold can be estimated using the systematic analysis of calcite twins, a few rock mechanics data characterizing the carbonates from the Madison Formation outcropping in the anticline and the chronology of the main fracturing events defined using the standard tool of structural geology. This analysis demonstrates that the growth of Sheep Mountain anticline induces a brutal release of 15Mpa of overpressure accumulated before folding during layer parallel shortening.

This innovative direct quantification of paleo-overpressure is compatible with present day estimates of in-situ stress and overpressure in similar tectonic context. It is compared with the evolution of the fracture patterns over Sheep Mountain. In particular, we can demonstrate that the overpressure release is contemporary of the formation of a very pervasive fracture set connecting the whole sedimentary sequence. This connection is further compatible with the evolution of stable and Sr isotope geochemical signature of cements precipitating within the veins

showing.

From a methodological point of view, we take advantage of this beautiful outcrop example to propose an operational workflow using mainly core data and log information to characterize paleo-stress and overpressure. We discuss the underlying hypothesis (paleo-depth hypothesis, calcite twin thresholds characterization) and the ongoing efforts to put this promising workflow on stream. From a geological point of view, this example is used to discuss the complex interplay between fracture network growth and overpressure build-up during the formation of fractured reservoirs.

Direct Paleo-overpressure Estimate, from Demonstration to Practical Application: The Sheep Mountain Anticline Example

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CASE STUDY SHEEP MOUNTAIN GEOLOGICAL SETTING

The studied fold is Sheep Mountain, an asymmetric basement cored anticline corresponding to a typical Laramide arch of the Bighorn Basin (Wyoming, USA) (Figure 1) (Hennier 1984).

It is affected by three main fracture sets (Figure 2). The first two ones were formed before folding as regional joints sets during layer parallel shortening related to Sevier (Set I) and then Laramide orogeny (Set II). The third one corresponds to outer arc extension veins formed during folding, parallel to fold axis (Set III).

Most of the presented data come from Carboniferous (Mississipian) limestones of the Madison formation outcropping in the core of Sheep Mountain Anticline (Figure 1).

Figure 1 SHEEP MOUNTAIN ANTICLINE

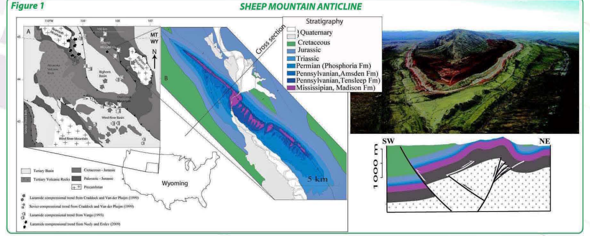
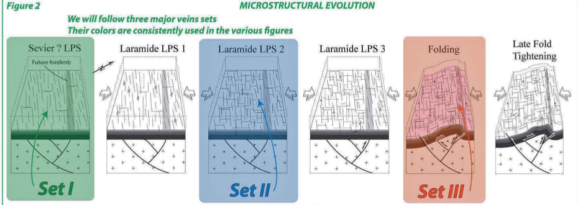


Figure 2 MICROSTRUCTURAL EVOLUTION

We will follow three major veins sets
Their colors are consistently used in the various figures



This scenario is defined in Bellahsen et al. 2006 and Amrouch 2010 et al. from field mapping of vein sets, fault kinematic analysis, calcite twin paleopiezometry and magnetic susceptibility anisotropy measurements all over the anticline

Figure 3 Typical evolution of vein sets and chronological constraints

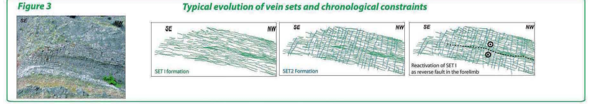
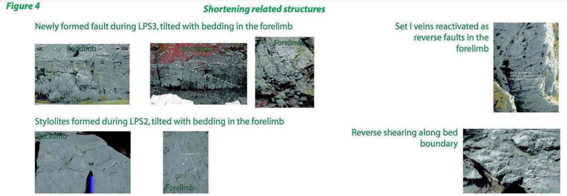


Figure 4 Shortening related structures



ABSTRACT

Geomechanical concepts and models play an increasing role in geoscience workflows, from exploration to reservoir management. This implies that new equations and parameters govern our earth models. Such models therefore request new data to be controlled. When it comes to mechanics in particular, it is crucial to rely on observations that control paleostress magnitudes. In this poster, we demonstrate how **paleo-stress and paleo-pressures** can be estimated in practice from the analysis of calcite twinning. This discussion is based on the study of an outcrop dataset, including structural and geochemical data to validate the proposed approach.

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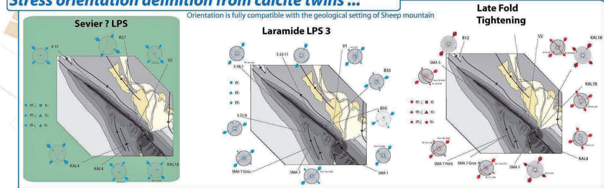
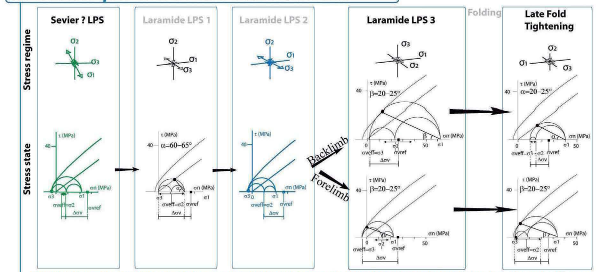
STRESS STATE EVOLUTION ESTIMATE

Stress orientation definition from calcite twins ...

Orientation is fully compatible with the geological setting of Sheep mountain



Stress state quantification from calcite twins ...



The Sevier LPS stage the principal stress magnitudes are constrained by the mode I opening of set I veins that contain σ2 axis after unfolding. The nearly 0.5 value of the stress ellipsoid shape ratio $\Phi = (\sigma_2-\sigma_3)/(\sigma_1-\sigma_3)$ leads to $\sigma_2 = \sigma_{veff} \sim$ 4-6 MPa.

The LPS1 stage corresponds to the left-lateral shear reactivation of preexisting set I veins.

LPS2 causes the opening of set II fractures, so the Mohr circle is tangent to the Crack Development Curve (CDC) at a point corresponding to the value of σ_3. $\sigma_{veff}=\sigma_2$ is constrained by a single value of Φ equal to 0.6.

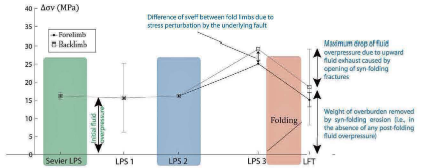
LPS 3 is a late LPS sub-stage associated with the maximum differential stress recorded by calcite twinning before folding. Occurrence of newly formed conjugate reverse faults (Fig 4. on the left) at 20-25° to σ1 axis requires that the (σ1,σ3) Mohr circle is tangent to the CDC. The Syn-folding stage corresponds to the opening of set III veins at the fold hinge and to slip on bedding surfaces in the fold limbs.

Late Fold Tightening with values of σ2 and σ3 close to each other, could explain how the strike-slip regime recorded by calcite twins caused the compressional reactivation of set I veins as small reverse faults in the forelimb. For the sake of simplicity, we consider that set I veins were reactivated when making an angle with σ1 axis equal to 20-25° (i.e., when tilted in their current attitude), but reactivation may have occurred earlier during folding.

PALEOPRESSURE ESTIMATES Confronted to geological observations

Using paleopiezometry, an overpressure drop ...

Each set is placed in the sequence according to the chronology of veins and their cements in which the calcite twin paleopiezometry is performed. Set III clearly corresponds to a pressure drop

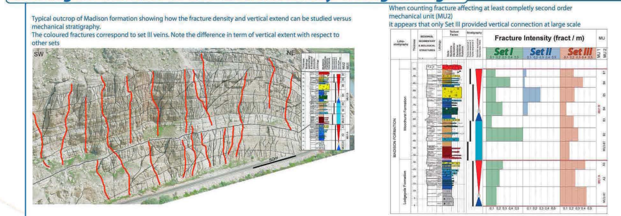


Choosing the reference value of the effective vertical principal stress by considering a pre-folding 2000m burial and an average density of the overburden of 2400 kg/m3 (see principle detailed on the rightmost panel), the calcite twinning paleopiezometry demonstrates that the end of the Laramide LPS phase corresponds to an overpressure climax reaching the lithostatic pressure. The formation of the third set that increases the vertical communication through the formation during folding induces a brutal release of this overpressure of at least 15Mpa. The coherency between three types of data (fracture stratigraphy, cement geochemistry, paleopiezometry) allows to demonstrate in Sheep Mountain anticline how fracturing stratigraphy can control paleo-hydrodynamics.

creating an increase of vertical connectivity during folding...

Typical outcrop of Madison formation showing how the fracture density and vertical extend can be studied versus mechanical stratigraphy. The coloured fractures correspond to set III veins. Note the difference in term of vertical extent with respect to other sets

When counting fracture affecting at least completly second order mechanical unit (MU2) it appears that only Set III provided vertical connection at large scale

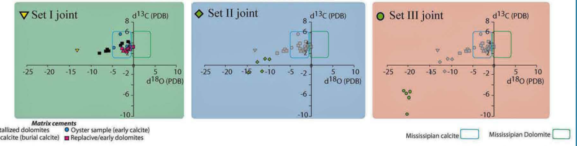


The quantitative study of the vertical connectivity and of the hierarchy of fractures allows constraining how the various vein sets have controlled the hydrodynamic communication during fold evolution. The analysis of the fracture network is based on more than 5000 bed confined fractures and 1000 large through going fractures, collected through more than 150 scanlines and representing a cumulated outcrop length of 8km.

Three order of fracturing can be described. The third-order corresponds to the bed-confined fractures, the first and second order to highly persistent fractures. First and second order fractures appear only during folding (third vein set).

induced contamination by deeper sources...

Geochemical evolution of the vein cements



The preserved fossils and early isopachous calcite cement exhibit an isotopic signature characteristic of marine Mississippian water. Eogenesis in muddy facies is characterized by an extensive dolomitization which isotopic signature indicates most probably a mechanism of seepage reflux from evaporitic layers located at the main sequence boundaries or a sebkha type deposition. The burial diagenesis is characterized by the precipitation of sparry calcite cement exhibiting a -6‰ to -8‰ in $\delta^{18}O$ average values and 4‰ to 2‰ in $\delta^{13}C$ average values. Compared to the marine values, this likely indicates an increase in temperature during burial. The cements in the early set I and set II are characterized by isotopic values which correspond to the late evolution of formation fluids. Conversely isotopic data of the cement in the synfolding set III (−20‰ for $\delta^{18}O$ and −5 to −10‰ for $\delta^{13}C$) point to a fluid contaminated by interaction with hydrocarbon but also warmer than the background temperatures of set I and II. The large shift in geochemistry evidenciate circulation at larger scale. This has been confirmed by fluid inclusion paleothermometry.

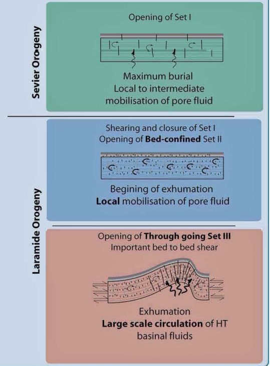
CONCLUSIONS

SHEEP MOUNTAIN Results

The facts presented in this poster allow to define the hydrodynamic evolution in relation to folding (scheme on the right).

The consistency of the gathered dataset demonstrates that:

- Tectonic compaction can induce overpressuring close to lithostratigraphic gradient.
- Calcite paleopiezometry can be used as a relevant indicator of paleo fluid pressure.
- Mechanical stratigraphy has a large impact on the hydrodynamic before folding.
- The tectonic regime during folding favours the vertical propagation of veins allowing the dissipation of overpressure. This dissipation should correspond to a significant rock hardening though most of the microstructures correspond to opening mode veins.

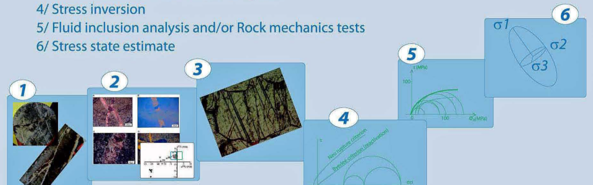


PRACTICAL APPLICATION

The practical estimate of paleo-stress states and paleopressures, will become very important to constrain geomechanical models used to improve basin modeling and fractured reservoir characterization workflow.

From the sheep mountain experience, the following workflow for paleopressures estimates can be proposed:

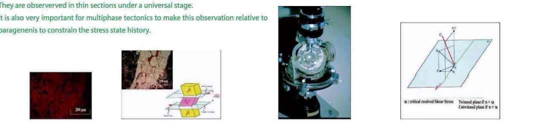
1/ Sampling oriented or re-oriented cores
(reorientation can be done using dip measurements or paleomagnetism)
2/ Description of the structural diagenesis on each sample
(fracture sets + cement history, generally already done for reservoir characterization)
3/ Identification of calcite twind in a set of calcite cristals representative of each cement
(this process can be automated using EBSD)
4/ Stress inversion
5/ Fluid inclusion analysis and/or Rock mechanics tests
6/ Stress state estimate



CALCITE TWIN PALEOPIEZOMETRY THEORETICAL BACKGROUND

5/6 components of the stress tensor from calcite twins

Mechanical e-twinning are widespread in calcite deformed at low temperature.
They are observerved in thin sections under a universal stage.
It is also very important for multiphase tectonics to make this observation relative to paragenenis to constrain the stress state history.



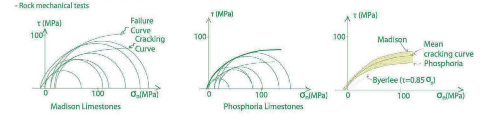
Twinning requires a low critical Resolved Shear Stress (RSS) (10 ± 4 MPa). Twinning is possible along three glide planes. Depending on the orientation of the principal stresses, twinning may occur on any or all of these twin planes.

We used Etchecopar's stress inversion to obtain the stress tensor (Lacombe, 2010 for a review). The inversion process takes into account both the twinned and the untwinned planes, the latter corresponding to planes that never experienced a resolved shear stress of sufficient magnitude to cause twinning. The problem consists in finding the stress tensor that best fits the distribution of twinned and untwinned planes. The basic hypothesis is that the resolved shear stress τ_s acting on any twinned e-plane is higher than, or at least equal to the critical RSS τ_a. Thus, for twinned planes: $\tau_s \geq \tau_a$ and for untwinned planes: $\tau_s < \tau_a$. This techniques allows to determine the orientations of the principal stresses σ1, σ2, and σ3 and the stress ellipsoid shape ratio .

The access to the 5th parameter of the tensor is possible because of the existence of a constant critical RSS τ_a : resulting in the estimate of (σ1-σ3) and (σ2-σ3).

the 6th component of the stress tensor

The estimate of the 6th component of the stress tensor requires an additional data to pinpoint the mohr circle.
Two can be used:
– Pressure estimate from fluid inclusion
– Rock mechanical tests

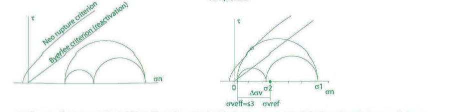


In the case of sheep mountain we use rock mechanics tests to characterize rock strength

Paleopressure estimate: principle

Step 1: Paleo stress orientation, and differential stress from calcite twin paleopiezometry (Lacombe, 2010 for a review)

Step 2: Hypothesis on burial depth gives σvref, type of rupture allow to choose fitting the neo-rupture or byerlee criterion. This gives Δσv as a proxy for overpressure



In this exemple corresponding to LPS3 in Sheep Mountain back limb, the mohr circle is shifted based on the fact new faults are created. It corresponds to compression tectonics, this allows to chose as sveff as s3

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