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Reconstruction of fluid (over-)pressure evolution from sub-seismic fractures in folds and foreland basins

Nicolas Beaudoin, Olivier Lacombe, Nicolas Bellahsen, and Laurent Emmanuel
UPMC, Université Paris 06, ISTeP UMR 7193, Paris, France

Deciphering the evolution of pressure, temperature and chemistry of fluids during fold history is a challenging problem. While temperature and chemistry of paleo-fluids can be determined using vein mineralizations in fault zones and/or in diffuse sub-seismic fracture sets, few methods exist to constrain the evolution through time of fluid pressure, especially when no hydrocarbons are encountered. This contribution aims at presenting and discussing a new approach to reconstruct the evolution of fluid pressure based on paleostress analyses.

The combination of stress inversion of fault slip data and calcite twin data with rock mechanics data allows determining both the orientations and the magnitudes of principal stresses during basin evolution. Assuming no burial change through time, the comparison of the computed magnitudes of the effective vertical stress with its theoretical value (calculated with respect to the paleo-overburden and hydrostatic fluid pressure) may be used to quantitatively estimate fluid overpressure in limestones at different steps of the tectonic history. Alternatively, if hydrostatic fluid pressure is assumed to prevail in the system from step to step, results likely reflect overburden variations.

The application focuses on the diffuse fracture populations observed in limestones of the famous Mississippian-Permian Madison and Phosphoria formations in Laramide basement-cored folds of the Rocky Mountains: the Sheep Mountain and the Rattlesnake Mountain anticlines (Bighorn Basin, Wyoming, USA). The location of these basement-folds on each edge of the Bighorn Basin ensures that depositional and erosional events can be neglected before folding, and thus grants the opportunity to constrain and to discuss the level of fluid overpressure during both the Sevier (thin-skinned) and Laramide (thick-skinned) related Layer-Parallel Shortening (LPS) phases at both fold scale and basin scale.

Results highlight an initial fluid overpressure in limestones buried at 2 to 3 km depth, and emphasize that the LPS-related stress build-ups during Sevier and Laramide are associated with an increase in fluid overpressure until it reaches the lithostatic pressure. In each fold studied, the evolution of fluid pressure however reflects peculiar periods during which tensile fracture and vein sets developed under a nearly hydrostatic fluid pressure, suggesting a high hydraulic permeability of the sedimentary cover. The hydraulic behavior of these tensile fracture/vein sets which formed during regional foreland flexure and at fold hinges in response to local strata bending is fully supported by independent geochemical studies performed on the cements of the same veins. At the basin scale, the evolution of the fluid overpressure possibly reflects the eastward fluid migration in the Rocky Mountain foreland during the Laramide contractional event. Finally, considering that fluid overpressure was released during folding permits to estimate syn-folding exhumation of strata, the value of which is consistent with independent paleo-barometric reconstruction based on hydrocarbon fluid inclusions and with exhumation-uplift rates derived from apatite fission-track data in neighboring Laramide uplifts.

To conclude, in a geological setting where the paleo-hydrological, the microstructural and the structural histories are well-constrained, we are now able to (semi-)quantitatively reconstruct the evolution of fluid (over-) pressure and to integrate this evolution in a consistent tectonic-fluid flow scenario at both fold scale and basin scale, to be compared with outputs of numerical modeling of fluid flow in basins.