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Contribution of studies of sub-seismic fracture populations to paleo-hydrological reconstructions (Bighorn Basin, USA)

Nicolas Beaudoin[a,b]*, Olivier Lacombe[a,b], Nicolas Bellahsen[a,b],
Laurent Emmanuel[a,b]

[a] *UPMC Univ Paris 06, UMR 7193, ISTEP, F-75005, Paris, France*
[b] *CNRS, UMR 7193, ISTEP, F-75005, Paris, France*

Abstract

This work reports on the reconstruction of the paleo-hydrological history of the Bighorn Basin (Wyoming, USA) and illustrates the advantages and drawbacks of using sub-seismic diffuse fracture populations (*i.e.*, micrometric to metric joints and veins forming heterogeneous networks), rather than fault zones, to characterize paleo-fluid systems at both fold and basin scales. Because sub-seismic fractures reliably record the successive steps of deformation of folded rocks, the analysis of the geochemical signatures of fluids that precipitated in these fractures reveals the paleo-fluid history not only during, but also before and after, folding. The present study also points out the need for considering pre-existing fluid systems and basin-scale fluid migrations to reliably constrain the evolution of fluid systems in individual folds.

Keywords: fluid system evolution; paleo-hydrological reconstruction; diffuse fracture network.

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1. Introduction

The interest of the Earth science community for the role of diffuse networks of sub-seismic fractures (e.g. joints/veins) on fluid flow in sedimentary strata is recent. Studies namely emphasize that fluid characteristics (temperature T, pressure P and chemistry X) evolve dynamically during folding [1], joints acting as efficient drains for fluid migrations especially in rocks with low matrix permeability (*e.g.* carbonates). According to mechanical stratigraphy, joints may allow fluids to migrate from deeper reservoirs toward overlying strata [2], sometimes overprinting the pre-existing fluid systems during folding (e.g. [1]). In contrast with major faults, sub-seismic fractures are common and accessible features

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* Corresponding author. Tel.: +33-1442-7781.
E-mail address: Nicolas.Beaudoin@upmc.fr.

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in sedimentary strata, and the associated mineralization grant an access to fluid migrations related to successive deformation stages [3]. Indeed, a fracture network observed in folded strata comprises various sets of fractures that may have formed before, during and after folding (e.g., [4]). The sequence of deformation based on sub-seismic fractures therefore provides a useful time frame for the evolution of the fluid system, including the fluid system that prevailed before folding and that may strongly impact later evolution [1]. Combining studies of the fracture sequence with the geochemical characterization of vein cements (∂^{18}O, ∂^{13}C, $^{87/86}$Sr) and with fluid inclusion microthermometry provides a powerful tool to unravel how P, T, and X of fluids evolved during deformation. To accurately constrain this evolution would be a major breakthrough to better predict fluid migrations in hydro-geological models and to document the degree of fluid-rocks interactions.

2. Geological setting and microstructural evolution

The Bighorn basin (BHB) is an extensively studied basin in the foreland of the Sevier–Laramide belt [5]. Fracture patterns and related fluid systems were investigated in five folds, especially in the Sheep Mountain (SMA) and the Rattlesnake Mountain anticlines (RMA) (Fig. 1b), where competent Carboniferous-Permian carbonate and sandstone rocks embedded within shales crop out. RMA provides access to the strata succession down to the Precambrian basement and to the underlying basement thrust.

The Sevier fracturing history comprises several sets of bed-perpendicular veins/joints (Fig. 1a): an E-W striking set S-I and a WNW-ESE striking set S-III reflect Sevier Layer-Parallel Shortening (LPS); in between, a N-S striking set S-II is related to the foreland bulge. Laramide bed-perpendicular vein/joint sets comprise a NE-SW striking set L-I related to LPS and a fold-axis parallel set L-II related to strata bending at fold hinge. A post-Laramide set P-I consists in persistent vertical joints/veins striking N-S.

3. Paleo-fluid systems in the Bighorn basin

∂^{18}O and ∂^{13}C values of vein cements reflect two different fluid systems depending on the fracture sets (Fig. 1c). ∂^{18}O signatures are homogeneous (set L-II in SMA, sets S-I, S-II in RMA, -22‰< ∂^{18}O< -17‰ PDB) or heterogeneous (-23‰ < ∂^{18}O < 1‰), the latter being interpreted as a mixing between reservoirs [6; 7]. These results, combined with temperature estimates based on microthermometry of fluid inclusions (bimodal distribution of 80°C and 130°C) and with $^{87/86}$Sr signal (Fig. 1e) constrain the scenario for the evolution of the fluid system [7]. The fluid system was closed (set S-I at RMA, Fig. 1c-1) until the development of joints related to the Sevier flexural forebulge (set S-II) caused vertical migrations of basement-derived fluids (Sr > 0,706; Th > 130°C) in the western part of the BHB (Fig. 1d-1). The eastward decrease of the Sr radiogenic signatures of vein cements suggests an eastward lateral migration of these basement-derived fluids thanks to the densification of the fracture network (Fig. 1d-2, e). This migration affected the paleo-fluid system prevailing before folding in the eastern part of the basin, which comprised at this time both basement-derived fluids and local fluids. During Laramide folding, a vertical pulse of basement-derived fluids is identified at SMA. Again, the curvature-related joint set appears to be the main conduit for these basement-derived fluids (Fig. 1d-3). In RMA, a third vertical pulse of such fluids is recorded during later extension, using related joints as drain.

A striking result is that joints formed in a strike-slip stress regime poorly increase the vertical hydraulic permeability. In contrast, joints formed in an extensional stress regime strongly increase the vertical hydraulic permeability, enabling vertical fluid flow and precipitation fast enough to limit mixing with local fluids and interactions with host rocks.

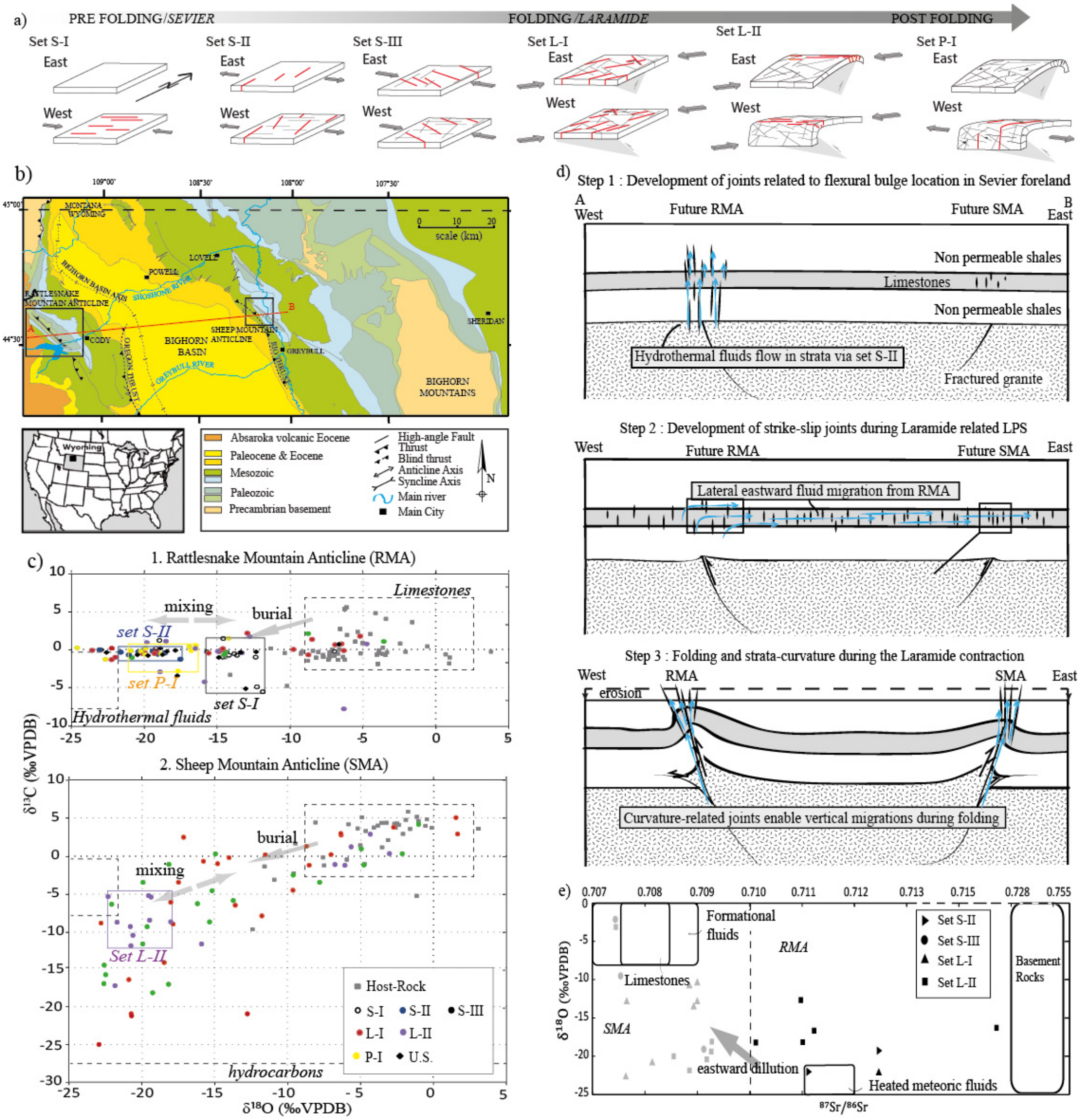

Figure 1: a) Sequential joint development in the BHB. b) Geological map of the BHB with location of SMA and RMA [8]. c) ∂^{18}O vs ∂^{13}C vs fracture sets [7]. Homogeneous sets are framed; geochemical end-members from the literature are framed with dotted lines. d) Schematic cross sections summarizing the three major events of the Sevier/Laramide paleo-hydrological evolution. e) ∂^{18}O vs $^{87/86}$Sr vs fracture sets in the BHB. End-members from the literature are framed [7].

4. Discussion and conclusions

This study shows that the evolution of the fluid system during folding greatly depends on the fluid systems that pre-existed in the strata. Because sub-seismic fractures are common and widely accessible in the field, they are the most reliable features to access fluid systems predating folding because they provide accurate time constraints on fluid flows, and grant an access to more numerous steps of deformation than the sole study of a fault zone. The upscaling of the results on fluid systems from an individual fold (SMA [6]) to the entire BHB [7] illustrates how the interpretation of a fluid system can change when data are integrated and interpreted at larger spatial and temporal scales. We believe that to efficiently reconstruct a paleo-fluid system in a fold and to understand the parameters that impact and control its evolution, it is essential to depict a large-scale overview of the paleo-fluid system in various positions in the basin and during the successive events of its tectonic history.

However, isotopic signatures of fracture population are often more scattered than those reconstructed in fault zones, because sub-seismic veins may also record local chemical variations and because of the uncertainties in attributing a given joint to a set based on its orientation only. This last limitation applies for instance to fold-axis perpendicular fractures, which could have developed at any time during folding [4]. To limit these uncertainties, other methods should be used, such as the determination of paleo-stress tensors from twinned calcite in vein cements (e.g. [8]).

A fundamental assumption in this work is that fluid precipitation is coeval with vein opening [1]. This synchronism must be constrained thanks to the mineralogical texture of the veins [3]: when they display fibrous crystals, the precipitation rate is equal to, or exceeds, the rate of opening. A blocky-type texture rather indicates fluid precipitation in a void, reflecting a fluid precipitation that postdates vein opening, or a coeval precipitation at a rate lower than the rate of vein opening. To test the synchronism, the precipitation engine should be considered. For calcite, it could be either the decrease in pCO_2 or an over-saturation of fluids in Ca due to fluids mixing, which implies pH-Eh variations [1, 9], both being possibly enhanced by fracture opening. Even though the development of a vein set may occur over the entire duration of the tectonic event to which it is related, we consider this development as nearly instantaneous during the folded rock history, so it makes sense to consider the precipitation of blocky calcite as reflecting the fluid system prevailing during the development of the fracture set. $\partial^{18}O$ and $\partial^{13}C$ signatures secure this interpretation. Using a reliable number of data, the mean isotopic signature of a fracture set likely reflects the fluid system active during its formation. Sets with heterogeneous isotopic signatures could reflect either fluid mixing or different episodes of cementation. We thus recommend to consider only veins with a single-phase filling, without evidence of reopening, and to use a representative number of data, both for chronological relationships between vein sets and for isotopic signatures.

Taking care of this, studying cements from diffuse vein networks provide a very powerful tool to reconstruct the paleo-hydrological evolution in thrust belts and foreland basins.

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