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Fracture-related fluid flow in sandstone reservoirs: insights from outcrop analogues of south-eastern Utah

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Fault- and fold-related fracturing strongly influences the fluid circulation in the subsurface, thus being extremely important for CO_2 storage exploration, especially in terms of reservoir connectivity and leakage. In this context, discrete regions of concentrated sub-parallel fracturing known as fracture corridors or swarms, are inferred to be preferential conduits for fluid migration.
We investigate fracture corridors of the middle-late Jurassic Entrada and Curtis Formations of the northern Paradox Basin (Utah), which are characterized by discoloration (bleaching) due to oxide removal by circulating CO_2- and/or hydrocarbon-charged fluids.
The analyzed fracture corridors are located in the footwall of a km-scale, steep normal fault with displacement values on the order of hundreds of meters. These structures trend roughly perpendicular and subordinately parallel to the direction of the main fault, defining a systematic network on the hundreds of meters scale. The fracture corridors pinch- and fringe-out laterally and vertically in single, continuous fractures, following the axial zones of open fold systems related to the evolution of the main fault. On the basis of the presented data we hypothesize that fracture corridors developed along the hinge of anticlinal/synclinal folds represent preferred pathways for fluid migration rather than the main faults, connecting localized reservoirs at different structural levels up to the surface.

Introduction

Fracture corridors are narrow and laterally extensive zones of concentrated fracturing defined by sub-parallel trending fractures (Ozkaya et al., 2007). Their width and lateral extension mostly depends on the generating process and the mechanical properties of the involved lithologies. From a practical point of view, these features are considered to strongly influence the fluid circulation in the subsurface, and are thus extremely important for hydrocarbon and CO_2 storage exploration in fractured reservoirs (Questiaux et al., 2010).

We here present data on fracture corridors characterized by ancient clues of fluid circulation that affect fine to medium-grained sandstones of the middle-late Jurassic Entrada and Curtis Formations of the northern Paradox Basin (Utah). The Entrada Fm. comprises mainly marginal, erg-type eolian sandstones, which have been transgressed by the predominantly tidal sediments of the Curtis Fm., through the development of a regional unconformity (Anderson and Lucas, 1994). Evidence of circulating fluids is provided by discoloration (bleaching) of the fractured lithologies, thought to be due to oxide removal by reducing fluids (i.e. hydrocarbon and/or CO_2-charged) (Dockrill and Shipton, 2010). Extensively bleached sandstones characterize wide intervals of the lower-middle Entrada Fm. succession, roughly defining ancient hydrocarbon/CO_2 reservoirs. The presented case study is from the northern part of the Salt Wash Graben (also known as Tenmile Graben), located ca. 12 km to the south of the Green River settlement. The analyzed area is in the footwall of a steep, km-scale, S-dipping normal fault (Salt Wash Fault) characterized by displacement values in the order of hundreds of meters. The alluvial/lacustrine, fine-grained lithologies of the early Cretaceous Cedar Mt. Fm. compose the hangingwall section.

Methods

Fracture corridors comprising associations of bed-confined and through-going fractures have been recognized, mapped and analyzed. Such fractures have been analyzed in terms of mesoscopic features (appearance, infilling material, involved lithology, character of surfaces) and geometric characteristics (azimuth, dip angle, spatial distribution). More than 40 scanlines for a total linear length of about 1 km have been measured at different stratigraphic levels and at different distances from the main faults to highlight the lateral/vertical variations of the structural attitude and arrangement of the bleaching. Detailed stratigraphic logs (1:50 scale) have been also measured to maintain the position of the measured scanlines within the succession and to characterize the sedimentologic/stratigraphic features of the involved lithologies.

Discussion and results

The observed fractures, showing only little or no displacement along their surface (joints), are locally arranged in seams and closely spaced parallel sets. This arrangement defines steep to vertical, roughly tabular to lenticular fracture corridors, usually characterized by bleaching haloes up to 1 m in width or more. Millimeter- to centimeter-thick bleaching haloes are also concentrated along single through-going fractures.

These structures trend mainly at high angle and, subordinately, roughly parallel to the main fault direction, pinching out laterally and up-section. This fracture network follows the axial zones of gentle, open fold systems, which are characterized by wavelengths and amplitudes on the order of hundreds and tens of meters, respectively. The transverse fold system develops almost perpendicularly to the main associated fault, with their axis trending at high angle to the fault strike and plunging away from its trace. Such folds are thought to be due to differential displacement rates along the fault strike, while the subordinate fault-parallel fold system could be due to fault-related flexural-rebound and minor antithetic/syntheric faulting (Schlische, 1995).

In the upper Entrada Fm. and the overlying Curtis Fm., bleaching is concentrated within and around fracture corridors and arranged as haloes surrounding isolated through-going fractures (Figure 1). Up- and down-ward fanning/fringing from the tips of fracture corridors has been observed within antiformal and synformal zones, respectively. Although the upper bleaching front of the lower-middle Entrada paleo-reservoir gently climbs up-section towards the main fault, there is few evidence of bleaching along the fault trace.

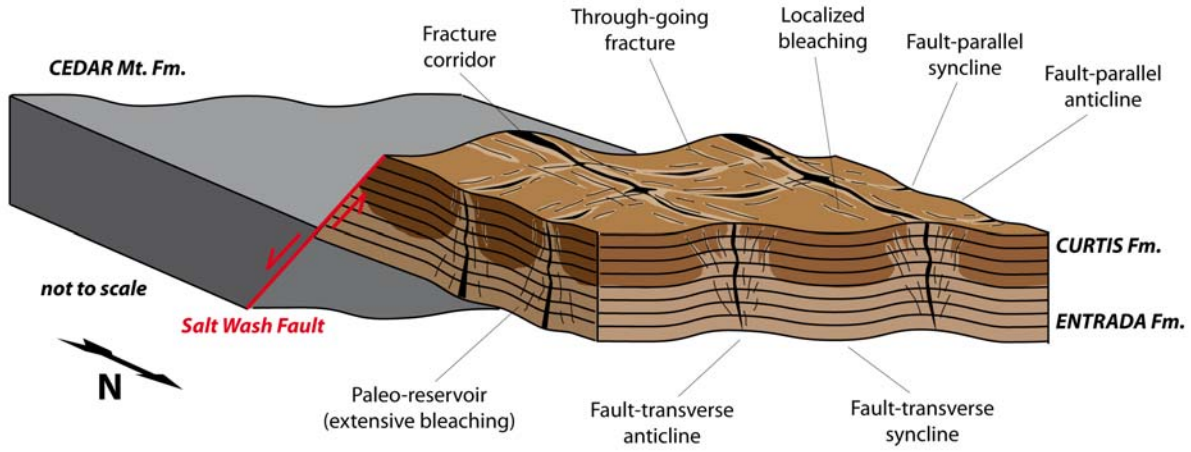

Figure 1 *Conceptual block diagrams of the high-permeable fracture network developed in the footwall of the Salt Wash Fault.*

Conclusions

We here point out the importance of fracture/joint corridors linked to normal fault-related folding as preferential pathways for vertical fluid migration rather than the main fault (Figure 1). This is possibly due to: 1) outer arc extensional regime maintaining fractures open along folds' axis, 2) clay smear development along the main fault trace, 3) fine-grained lithologies in the hangingwall, and 4) focused flow into the cores of folds.

Such high permeability zones trend roughly perpendicular, and subordinately parallel to the main associated fault, which instead baffles lateral fluids migration. The recognition of these structural features is thus important for a correct understanding of subsurface fluid flow, especially to characterize the connectivity of fractured reservoirs and to assess risk of leakage from potential CO_2 storage sites.

Acknowledgments

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