Do Subsurface Models Accurately Represent the Rock? Insights from Outcrop on the Often Overlooked Importance of Mechanical Stratigraphy*

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Abstract

A valid subsurface structural geologic interpretation should (i) honor available subsurface data (e.g., well and seismic), (ii) incorporate structural styles known or expected for the mechanical stratigraphy and deformation conditions in the region, and (iii) be logically restorable to an original unstrained condition. In many cases, multiple interpretations can be developed that honor the available data, but the geology is fixed. A crucial part of any interpretation exercise is the ability of the interpreter to know what is possible and what is not based on the constraints of the data.

H. H. Read said that "the best geologist is the one who has seen the most rocks." Whether or not that is true, it seems to be true that the more rocks a geologist has studied in the field, the more options that person will consider and test when developing subsurface interpretations for a given set of data. Structural style is highly sensitive to the mechanical stratigraphy and deformation conditions (including tectonic stress regime, stress state, fluid pressure, and temperature). In our work in a range of tectonic regimes and across scales, we find that mechanical stratigraphy has predictable influences on the structural style at seismic and subseismic scales.

Here we examine two cases in Cretaceous carbonate strata in central and west Texas deformed in extensional and contractional tectonic settings, where outcrop characterization provides insights into the influence of mechanical stratigraphy and structural position on seismic- and subseismic-scale deformation in the layers. These examples illustrate the utility of considering how mechanical stratigraphy influences the development of different deformation styles, even where deformation conditions are otherwise similar.

Case 1: Extensional System

Exposures of normal faults in Cretaceous carbonates of central and west Texas provide excellent laboratories for understanding fault-zone architecture and deformation (Figure 1). Mechanical stratigraphy is a fundamental control on carbonate fault zones (Ferrill and Morris, 2008; Ferrill et al., 2007, 2009, 2011; Morris et al., 2009; Smart et al., 2012):

- Relatively planar faults with low-displacement gradients develop in massive, strong, clay-poor limestones and dolomites, and faults tend to be steep (70° or more).
- In less competent clay-rich strata, shale beds impede fault propagation, resulting in normal-fault-related folding with locally steep bedding dips, and faults will have shallower dips (60° or less).
- In mixed stratigraphic sequences, the ratio of incompetent to competent strata is a useful guide for determining the most likely structural geometry, which will be a hybrid of the two end-members described above.
- Competent strata have low displacement-to-propagation ratios and will inhibit fault-related folding.
- Incompetent strata have high displacement-to-propagation ratios and will promote fault-related folding.

A seismically resolvable normal fault cutting a mechanically layered sequence of rocks, represented by competent, incompetent, and mixed competence packages, is likely to have dramatically different fault-zone deformation styles. Although not necessarily resolvable at the seismic scale, these fault-zone deformation styles are predictable based on knowledge of the mechanical stratigraphy and deformation conditions, and they have important implications for the migration and trapping of hydrocarbons, as well as reservoir and well performance.

Case 2: Contractional Setting

Small-displacement faults and extension fractures are critical to porosity and permeability as well as reservoir performance. The Persimmon Gap anticline (Figure 2A) is a Laramide hanging-wall anticline above the Santiago Thrust at the northeastern entrance to Big Bend National Park, Texas. In the core are refolded Paleozoic rocks that are unconformably overlain by Cretaceous rocks. Two contractional deformation events are recorded in the rocks: (i) a Late Paleozoic Ouachita event that overturned and faulted the Paleozoic sedimentary rocks, and (ii) a subsequent Late Cretaceous Laramide event that re-folded the Paleozoic rocks and folded and thrust-faulted the Cretaceous rocks. The overturned forelimb contains numerous extensional features that indicate the fold is not a simple single-step fault propagation fold, but one that has experienced forelimb extension and thinning as a result of limb-locking during folding. Joints are ubiquitous around the anticline; however, calcite extension veins and bed-extending faults are common in the forelimb and the crest of the fold but are absent from the backlimb and regions of high curvature.

Geomechanical modeling (Figure 2B), using field observations to inform the models (e.g., relative strength profiles, presence or absence of bedding parallel slip, and direct measures of geologic strain) can be used to predict the onset of failure and the location, type, and abundance of deformation features (e.g., Smart et al. 2009, 2012). This approach complements outcrop-based structural observations, and builds confidence in the use and interpretation of geomechanical models, when appropriately constructed.

Specific conclusions drawn from this study are that outcrop and model results show that an understanding of mechanical stratigraphy is central to predicting where deformation features that might affect reservoir performance (e.g., faults, fractures, tectonic stylolites) may develop.

Mechanical stratigraphy is a first-order control on structural style at the seismic and subseismic scale, and it deserves priority attention during training of geologic interpreters.

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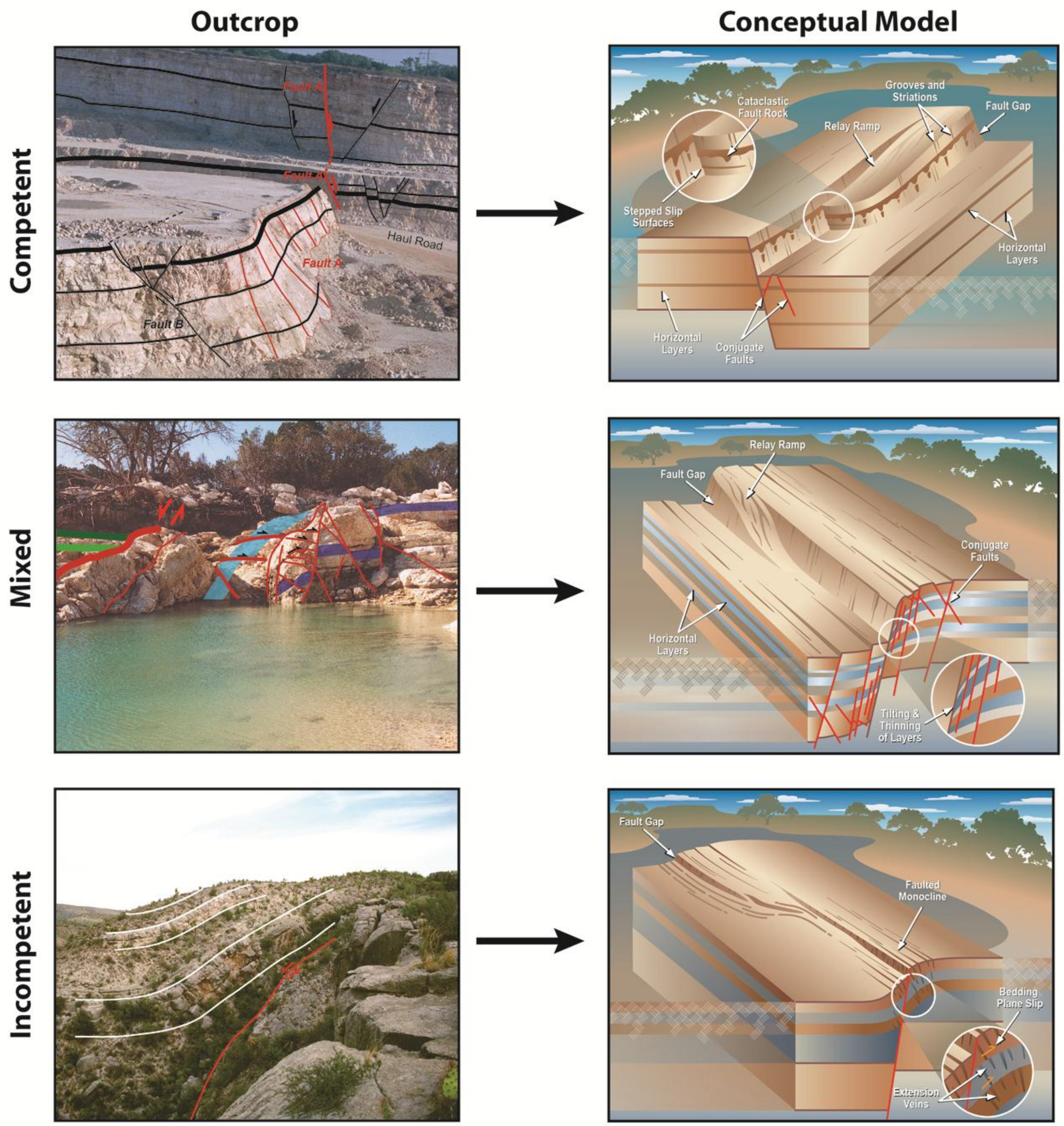

Figure 1. Outcrop characterizations led to the construction of conceptual models showing the influence of mechanical stratigraphy on structural deformation for mechanical stratigraphic units with variable incompetent to competent thickness ratios (after Ferrill and Morris, 2008; Ferrill et al. 2007, 2009).

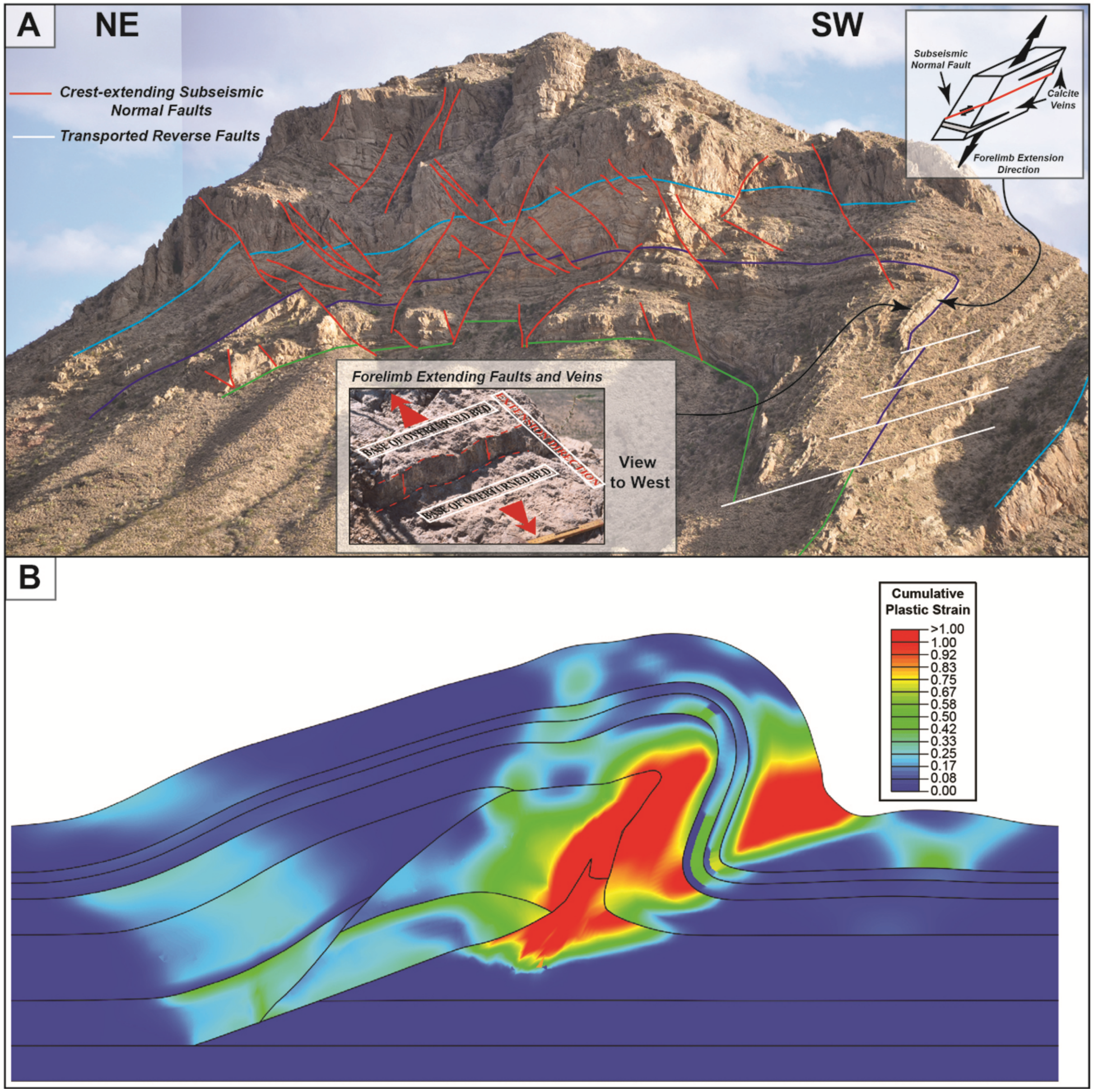

Figure 2. A. The Laramide anticline exposed at Persimmon Gap is a seismic-scale, transported chevron fold with a gentle plunge to the southeast. B/ Finite-element model results of a contractional fault-related fold showing contours of cumulative permanent strain superimposed on the deformed geometry (after Smart et al. 2012).