The Influence of Mechanical Stratigraphy on Joint Networks Development

By: Zainab Al Ibrahim, Geologist at Saudi Aramco

Mechanical stratigraphy is defined as variations in mechanical properties of different rock units across the same lithostratigraphic column. Understanding these variations can offer in-depth knowledge of rock behaviors for fractures and joint networks characterization. These mechanical properties include tensile strength, elastic-plastic response, and fracture susceptibility. Each mechanical stratigraphic unit is a product of chemical and mechanical changes on the rock from sedimentation to the present day. Although mechanical stratigraphy is related to lithology, the description of lithology solely does not always reveal the rock's mechanical properties (Figure 1).

The presence of distinct lithologies or structural discontinuities within a stratigraphic unit dictates changes in mechanical stratigraphy. Both layer thickness and rigidity contrast drive mechanical stratigraphy variations, resulting in distinctive rock responses regardless of similarities in depositional environments. This article will highlight the influence of mechanical stratigraphy on deformation styles and lithological variation effects. It will also demonstrate a machine learning application for an efficient identification of mechanical stratigraphy.

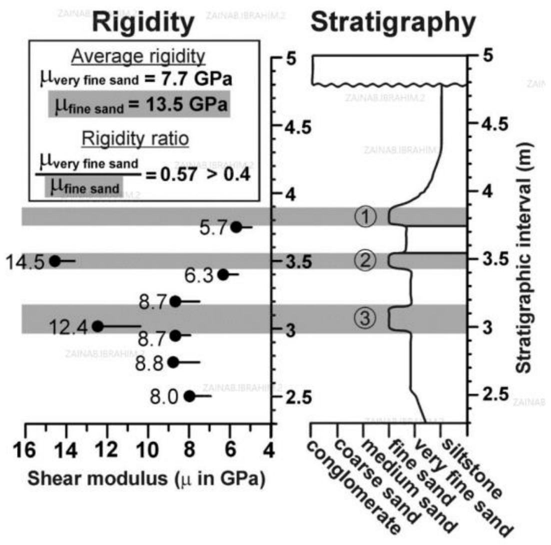

Figure 1: Mechanical stratigraphic profile shows rigidity contrasts correlated with stratigraphy and values of shear modulus. (Shackleton, 2005)

Lithological Variations Effect on Deformation Styles

Understanding the influence of mechanical stratigraphy on folds development and geometry requires an in-depth analysis of both the elastic-plastic deformation model and contrast coefficients of adjacent rock layers. Many thrust belts structural deformation occurs when certain layer arrangements exist; which consist of: a weak underlying layer (shale or salt), a strong middle layer (carbonate), and a top cover layer (clastic) (Fig.2). This specific arrangement, along with slip components, enhances folding over faulting in many thrust deformation zones worldwide. In most cases, high strength contrast in mechanical stratigraphy strongly impacts the overall shape.

The presence of a salt layer can be a critical component in the evolution of structures in settings like folds and thrust belts. The deformation geometry is highly influenced by the contrast variation between weak and strong rock layers. Salt is known to be two times weaker than most rock types, and therefore when a décollement develops within a salt layer (i.e., horizontal gliding between two rocks) beneath an existing fold or thrust belt, salt promotes a higher degree of folding. The presence of salt strongly impacts deformation styles, unlike cases in which a salt layer does not exist. The degree to which these layers contrast may favor folding over faulting is exclusively dependent on the mechanical rock properties. For example, at high strain settings, a thick strong rock layer experiences high fold amplification, as strong layers tend to reach the maximum strength point faster than weak layers, and subsequently result in shortening and weakening of that specific layer without breaking into segments.

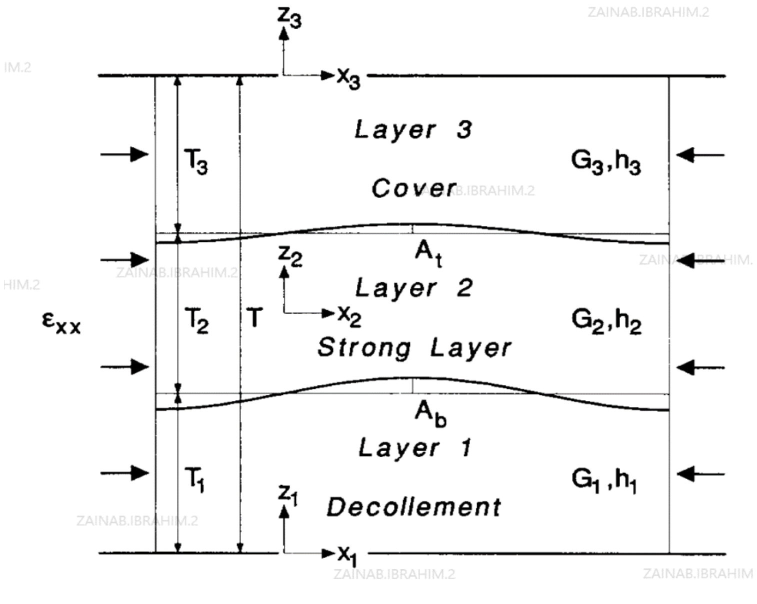

Figure 2: A three-layer arrangements model indicates a weak décollement layer (bottom) experience shortening, underlying by a strong layer (middle) and a cap layer (top). The diagram shows different mechanical properties of materials, where bottom layer has no shear stress or vertical component of displacement. Top layer experiences no stress from other overlaying surfaces (G: elastic shear modulus with X and Z component, H: plastic hardening modulus, T: total thickness, T1, 2, 3: layer thickness). (Erickson, 1995)

Effect of Mechanical Stratigraphy on Joint Network

Mechanical stratigraphic contrasts highly influence joint propagation patterns. These patterns are used to interpret rigidity contrasts and changes in mechanical properties due to diagenetic alterations. Observations of joint patterns, namely bed-contained joints (first event), and through-going joints (a second event that exhibits different orientations), suggest changes in mechanical stratigraphy and the existence of two fracturing events over time (Fig.7). Bed-contained joints formed when rigidity contrast was higher than it is today, while through-going joints indicate low rigidity contrast and preservation of present-day conditions. Different stages of diagenesis affect mechanical properties based on composition, grain size, and compaction. These alterations in mechanical stratigraphy affect joint networks and the overall rock behaviors.

Mechanical conditions do not remain the same, especially if the lithological units experience multiple fracturing events. The mechanical stratigraphy profiles change due to diagenetic processes, which can lead to new 3D joint networks. Sometimes these joint networks act as fluid conduits and enhance the migration process for hydrocarbons, but due to the constant change during diagenesis, these joint networks' effectiveness in the petroleum system can change through geologic time. During deformation, rocks undergo different degrees of diagenesis, and as deformation continues, the beds containing initial joints may get rotated. In this case, these joint networks no longer preserve the original joint network orientation and properties.

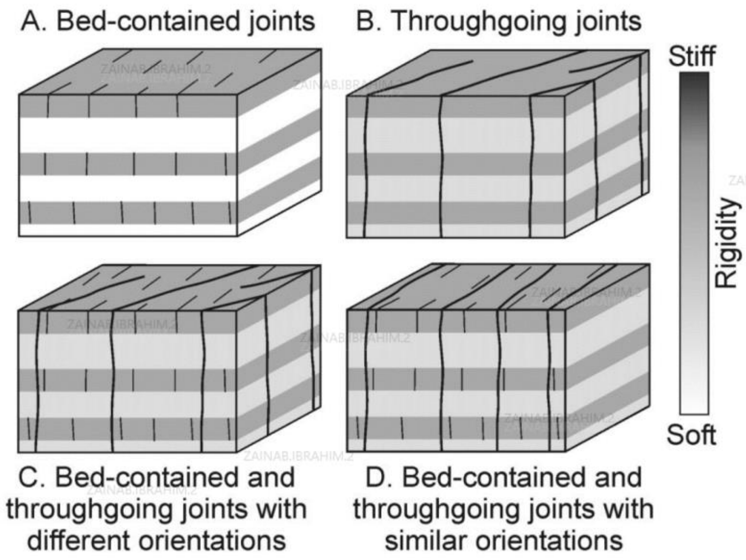

Figure 3: Single joint patterns with constant mechanical stratigraphy (A and B) and double joint patterns with varying mechanical stratigraphy (C and D). Bed contained joints formed at high rigidity contrast (A), while through-going joints formed at low rigidity contrast (B). Illustration of different joint patterns (C and D), as bed contained formed first at high rigidity contrast (primary joints event), then through-going joints at low rigidity contrast (second joints event). C and D are similar, except that C beds got rotated after the first jointing event, resulting in different pattern orientations. (Shackleton, 2005).

Mechanical Stratigraphy Effect on Normal Faults Geometry

The geometry of normal faults is related to the lithological contrast and competency between rock layers which determine propagation (Fig.4). Two main factors affecting fault propagation 1) interface strength and 2) contrast of rheology. A weak rock interface favors fault propagation. This is true for soft and ductile layers. On the other hand, strong rigidity contrast promotes fault termination. Wide fault zones commonly develop when the incompetent/competent ratio equals 1.4 or higher, while narrow fault zones appear if the ratio is 0.07 or less.

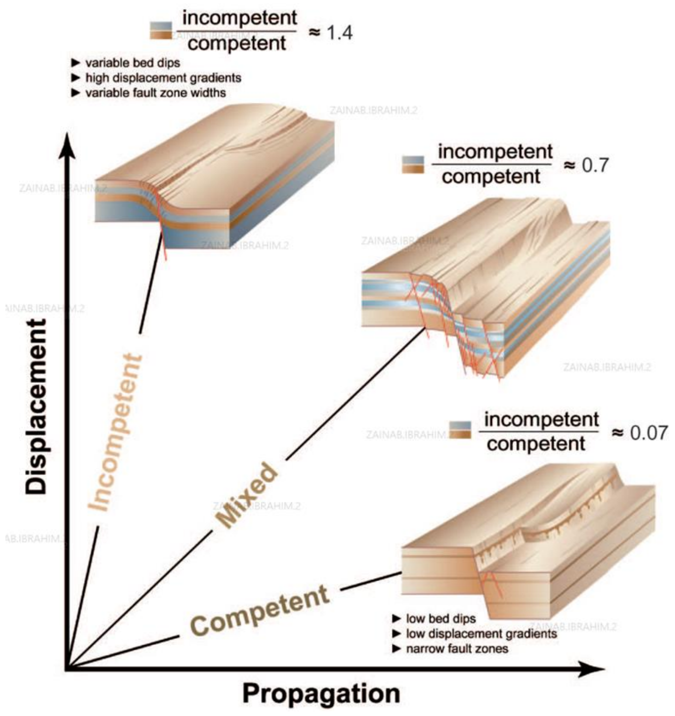

Figure 4: Schematic illustration shows the influence of mechanical stratigraphy and the incompetent to competent ratio for normal faults geometry. Usually, high propagation compared to displacement is common for faults with high competent layers. Both bed dips and the incompetent to competent ratio is low (0.07). On the other hand, high incompetent to competent ratio (1.4) has high displacement compared to the propagation and almost near-vertical displacement gradients. (Ferrill, 2008).

Application of Machine Learning for Mechanical Stratigraphy

One of the limitations of direct mechanical data is that they are usually discrete points and do not necessarily sample the entire section of interest. Machine learning algorithms can be leveraged to detect and visualize differences in mechanical stratigraphy through K-mean clustering. A machine learning workflow analyses lab-measured geomechanical data and clusters them into multiple categories based on visual image characteristics (i.e., RGB components). Later, support vector regression (SVR) is used to link specific mechanical values such as E-static and shear modulus with rock strength and lithology (Fig.5).

Machine learning applications of mechanical stratigraphy identification is implemented to classify lithology contrasts and help predict rock behaviors. This approach is cost and time effective for determining rigidity contrasts and rock strength, with minimal lab testing and rock destruction, after aggregating enough training dataset. The final outcome is a continuous high-resolution mechanical stratigraphy profile which then can be an important input in fracture characterization and subsequently helps in stimulation and development decision making.

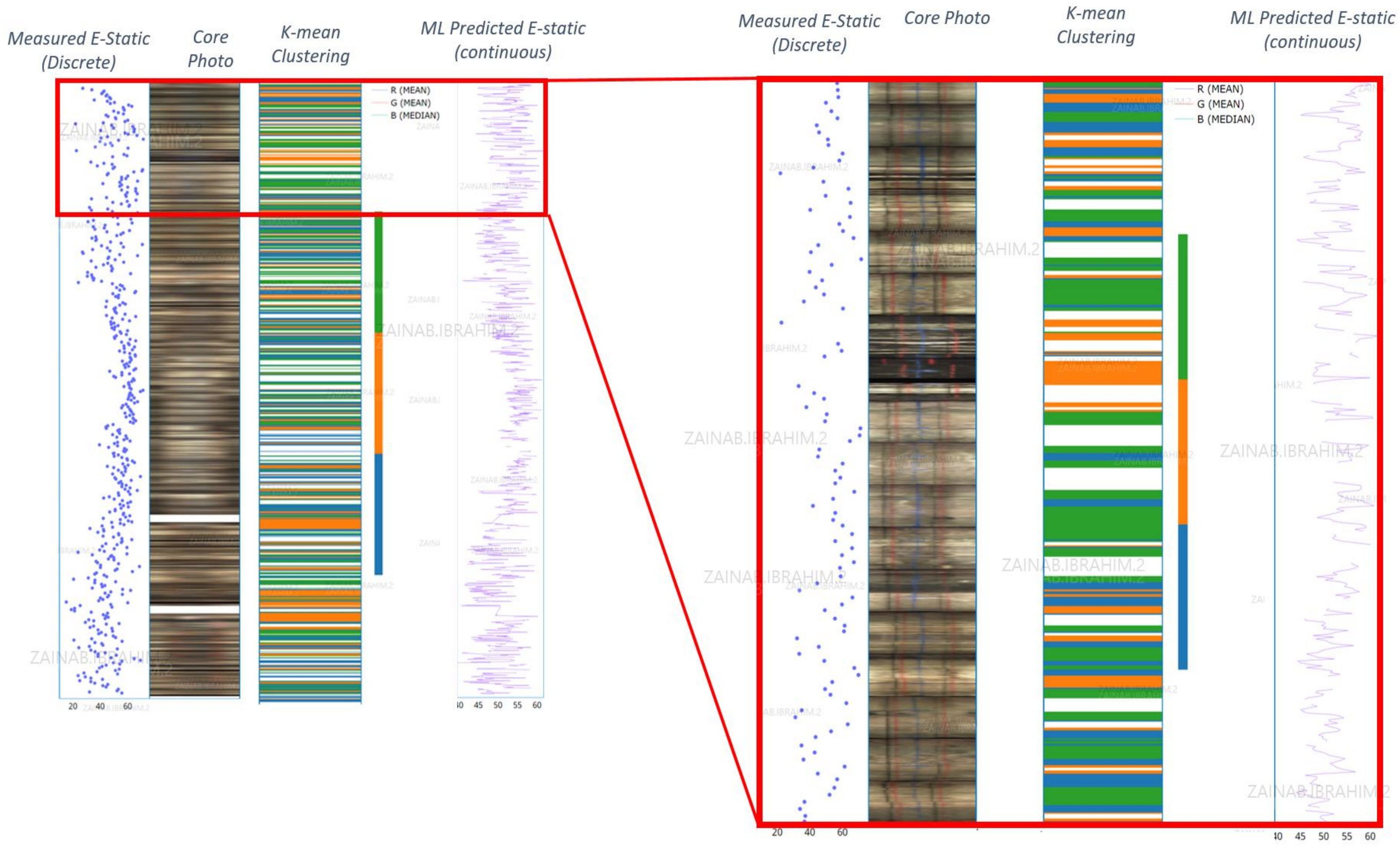

Figure 5: Machine learning application of clustering mechanical data. Core photo along with discrete lab measurements of E-static (GPa) (Right) K-mean clustering of rock types into groups based on image characteristics (RGB) using machine learning workflow (Middle) continuous high-resolution prediction of E-static curve (GPa)(Left).

Conclusion

Mechanical stratigraphy can be defined by different factors, including rock rigidity, relative thickness of each bed, and the interference contrast between layers. The presence of different lithologies within a stratigraphic unit determines variations in mechanical stratigraphy. These mechanical stratigraphic variations are products of both chemical and mechanical changes on the rock since depositional time.

To understand deformation styles development and geometry, it is critical first to analyze the elastic-plastic deformation model and detect changes in mechanical stratigraphy. These changes are controlled by different layer thickness and rigidity contrast and therefore result in distinguished rock responses and deformation styles such as joint networks and faults.
Although lab and field mechanical stratigraphy data provide a good understanding of rock behaviors, using machine learning applications to identify, quantify, and predict mechanical stratigraphy can be a cost and time effective tool providing inputs and parameters to enhance fracture characterization and field development.

References

Erickson, S., 1995, Influence of Mechanical Stratigraphy on Folding Vs Faulting, Journal of Structural Geology

Ferrill, D., Morris, A., 2008, Fault Zone Deformation Controlled by Carbonate Mechanical Stratigraphy, Balcones Fault System, Texas, The American Association of Petroleum Geologists Bulletin

Shackleton, J., Cooke, M., Sussman, A., 2005, Evidence for Temporal Channing Mechanical Stratigraphy and Effects on Joint-Network Architecture, Geological Society of America

DGS
DHAHRAN
GEOSCIENCE SOCIETY