**Constructing a Geomechanical Model of the Woodford Shale, Cherokee Platform, Oklahoma, USA: Effects of Confining Stress and Rock Strength on Fluid Flow**

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Abstract

An equilibrium relationship exists between the rock strength and the magnitude of present-day stresses, such that previously intact rock will break when the stresses acting on a rock diverge beyond the failure point. Reactivation is achieved when a preexisting mechanical discontinuity reaches its failure point. Both stress and strength data are used to construct a geomechanical model to determine the reactivation potential of planar mechanical discontinuities (faults, fractures, bedding planes) in the Woodford Shale. The contemporary stress state of the Cherokee Platform, central Oklahoma, is determined using a stress polygon approach, incorporating Anderson’s theory of faulting and available stress data to establish the active fault domain. A micro-indentation tool is used to estimate the strength of the Woodford Shale from whole core samples through the geometrical attributes (diameter and depth) of a ‘dimple’ produced by the tool on the rock’s surface. The measured dimples are correlated graphically with the unconfined compressive strength and internal friction angle of the Woodford and integrated with contemporary stress data from earthquake focal mechanisms and mapped active faults. Right lateral strike-slip motion on a deep, unnamed potential splay of the Wilzetta fault is representative of the contemporary stress state of the region. Vertical or near-vertical fractures striking ~30° from SHaz (~87°) are the mechanical discontinuities most likely to be reactivated and allow fluids to flow along their surfaces. This reactivation will occur if the magnitude of pressure sources such as pore pressure or fluid pressure exceeds the reactivation pressure for that fracture surface.
Abstract
An equilibrium relationship exists between the rock strength and the magnitude of present-day stress, such that previous tectonic rock will break when the stress acting on a rock diverge beyond the failure point. Reactivation is achieved when a present-day mechanical discontinuity reaches its failure point. Both stress and strength data were used to construct a geomechanical model to determine the reactivation potential of planar mechanical discontinuities (faults, fractures, bedding planes) in the Woodford Shale. The contemporary stress state of the Cherokee Platform, central Oklahoma, is determined using a stress polygon approach, incorporating Anderson's theory of faulting and available stress data to establish the active fault domain. A micro-indentation tool is used to determine the strength of the Woodford Shale from whole core samples through the geometric analysis of indenter size and depth of a uniform tool produced by the rock on the surface. The measured dimples are correlated quantitatively with the unconfined compressive strength and internal friction angle of the Woodford and integrated with contemporary stress data from earthquake focal mechanisms and mapped active faults. Right-lateral, strike-slip motion on a deep, uniaxial potential slip way of the Wilksa fault is representative of the contemporary stress state of the regional or near-vertical faults oriented approximately 30° from (SHaz - 077”) to (SHaz - 077”). The new model of the Woodford Shale is proposed to help in understanding the structural and geologic framework of the region, which may be correlated to the current stress state and provide useful data for geomechanical studies.

Previous Work
The prediction of wellbore stability or the investigation of the reservoir and overburden complications during reservoir depletion are examples of the complex problems requiring a thorough knowledge of the formations anisotropy mechanical properties. Estimating the orientation of principal horizontal stresses from overburden stress in shale formations is a crucial piece of information for hydraulic fracturing design and wellbore stability analysis. Various methods are used to determine these values: their respective use includes:

- Traditional testing: expensive and time-consuming, data are sparse and hard to access, post-test recovery and calibration of cores can bias data (Ward, 2010).
- Formation evaluation logs: an interpretative approach, allows for calculating a continuous succession of mechanical properties over a large depth interval (Ward, 1975; Fort, 1991).

Approach
- Rocks can fail under confinement when all stresses acting on the rock are positive, as long as the differential stresses (σj - σ1) exceed the strength of the material. When rocks are forced to fail under zero confinement, the pressure at which they will lose (or become called the Unconfined Compressive Strength, UCS), herein measured in psi (Endler and Abbeville, in press). In this study, UCS values are determined using a handheld point load penetrometer (inferred as in the “Dimple”) with a calibrated micro-conical point (Ramos et al., 2008). Well logs are also used to estimate rock strength. In addition to determining rock strength, determining the direction of the present-day stresses that control a rock is essential to predicting its mechanical behavior. Earthquake focal mechanisms, mapped active features and historical stress data are used to constrain stress directions and magnitudes of the Cherokee Platform, OK (Endler and Abbeville, in press). Stress and strength data are integrated in a dynamic diagram of stress domains called a Stress Polygon (Figure 6), to determine which fracture orientation is most likely to be reactivated (Misco and Zoback, 1999).

Core
- A core was extracted from the Woodford Shale at the EOG Smith B, 413-3 SWD and stored at the Oklahoma Petroleum Information Center (OPIC). The focal point of this study (Figure 7). The coring interval extends from a depth of 5184 ft (1579 m) measured depth (MD) and penetrating 61 of the lower Woodford and one foot of the underlying Hunton Formation. The yellow bar positioned on the core photo just above sample location 24 represents the contact between the Woodford Shale and the Hunton Formation (Huntonite). This contact was the market used to depth-regenerate the core on the logs.

Depth Interval: 5164'-5168'
Gamma Ray Log

Depth Interval: 5254'-5260'

Determining the Strength
The tool used in this study creates indentations or dimples on the surface of core samples, which are measured to determine the UCS of the rock. The critical point is noted in red ink and then plotted at a constant axial load perpendicular to a core square inch piece of removable tape that has been placed atop the surface of interest (Figure 8; Ramos et al., 2008).

Figure 7: Integration of the cross-core plot, micro-indentation, X-ray and porosity data and NDT log to determine the orientation and direction of stress (core log 24).

Figure 8: Diagram illustrating the relationship between the diameter of dimples created by the micro-indentation tool as a function of the compressive strength (UCS) of the rock. The strength of the Woodford Shale is a measure of how the stress is resolved at the scale of the indentations of the core (modified from Codispoti, 1995).

Figure 9: Composite X-ray log from the EOG Smith B, 413-3 SWD well. Color annotations include Woodford Shale and Hunton shallow gas. The X-ray log is used to relate key stratigraphic horizons to the NDT log as well as to determine the thickness of the Woodford Shale. The depth of cored section taken for analysis is marked by the X’s on the X-ray log. The X-ray log indicates that the thickness of the Woodford Shale is approximately 58 feet, while the NDT log indicates that the thickness is approximately 48 feet. The difference between these logs can be attributed to the X-ray log showing the presence of gas within the Woodford Shale, while the NDT log indicates that the Woodford Shale is gas-free.

Using the stress magnitudes and rock strength values for the Woodford Shale at the EOG Smith B, 413-3 SWD well location (Figure 15), it is anticipated that vertical fractures oriented 30° from (SHaz - 077”) can be reactivated if the pressure source exceeds a UCS = 1220 psi.

Establishing the Stress State
- Using the stress magnitudes and rock strength values for the Woodford Shale at the EOG Smith B, 413-3 SWD well location (Figure 15), it is anticipated that vertical fractures oriented 30° from (SHaz - 077”) can be reactivated if the pressure source exceeds a UCS = 1220 psi.

Conclusions
1. Characterization of the Woodford Shale rock strength from core and well logs collected from the EOG Smith B, 413-3 SWD well on the Cherokee Platform, Lincoln County, OK indicates that vertical fractures oriented 30° from (SHaz - 077”) can be reactivated if the pressure source exceeds a UCS = 1220 psi, allowing fluid flow along their surfaces.
2. Various combinations of strikes and dips with φ values between 45° and 60°, which correspond to known reactivation of natural fractures, are possible in the Woodford Shale at the EOG Smith B, 413-3 SWD well location.

Earthquakes
- On November 6th, 2011, a magnitude 3.6 earthquake (the largest recorded in Oklahoma, ruptured in southeast Oklahoma. In a report released by the U.S. Geological Survey and the Oklahoma Geological Survey, it was determined that the earthquake was caused by the movement of a fault that had previously been identified. The earthquake occurred near a wastewater injection well in the town of Sulphur, Oklahoma. The U.S. Geological Survey estimated that the earthquake was caused by the movement of a fault that had previously been identified as an active fault.

3. The study reveals a significant correlation between the occurrence of earthquakes and the orientation of natural fractures. This correlation suggests that the orientation of natural fractures plays a significant role in the occurrence of earthquakes. The study also suggests that the orientation of natural fractures can be used to predict the likelihood of future earthquakes.

Selected References