PS 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 factures 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.

Constructing a Geomechanical Model of the Woodford Shale, Cherokee Platform, Oklahoma, USA

Effects of Confining Stress on Rock Strength and 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 factures oriented ~30° from SHaz (~77°) 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.

Depositional Setting

The Cherokee Platform, Oklahoma, USA is a Paleozoic structural high separating several petroleum producing basins from one another, including the Anadarko, Marietta, Ardmore and Arkoma basins. Depositional cycles of carbonate and clastic rocks were strongly influenced by subsidence rates (Sutherland, 1989). The Woodford Shale (Middle Devonian to Early Mississippian) was deposited atop a major regional unconformity, and is lithologically comprised of black shale with interbedded chert and siltstone, commonly altered diagenetically by pyrite, phosphate and cements (Figure 3) (Johnson, 1985; Comer, 2008).

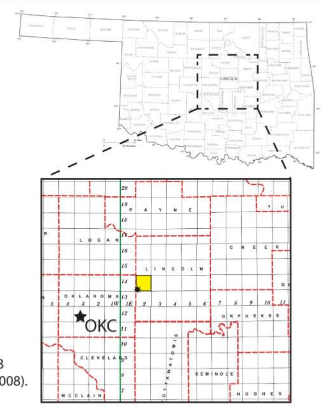


Figure 1: Study area showing the EOG Smith, B. 31 #3 SWD core location, 31-14N-2E (modified from OGS, 2008).

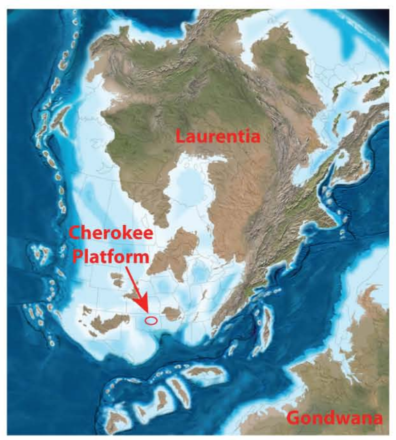


Figure 2: Late Devonian (360 Mya) paleogeographic map depicting the active collision of Laurentia and Gondwana (modified from Miall and Blakey, 2010).

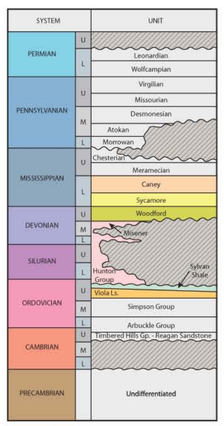


Figure 3: Generalized stratigraphic nomenclature for central Oklahoma (modified from Charpentier, 2001).

Structural History

The Nemaha Trend is a buried, uplifted ridge in central Kansas and Oklahoma. Bi-directional thrust faults formed v-shaped "pop-up" blocks, which were offset by left-lateral strike-slip faulting during the Ouchita Orogeny (Gay, 2003). Contemporary right-lateral strike-slip faults have been identified using seismic surveys and earthquake focal mechanisms (Holland, 2012).

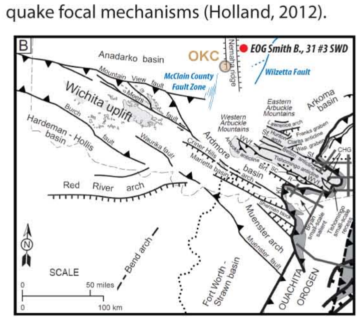


Figure 4: Pre-Mesozoic Oklahoma geologic map. Active faults referenced in this study are colored blue (modified from Jusczuk, 2002).

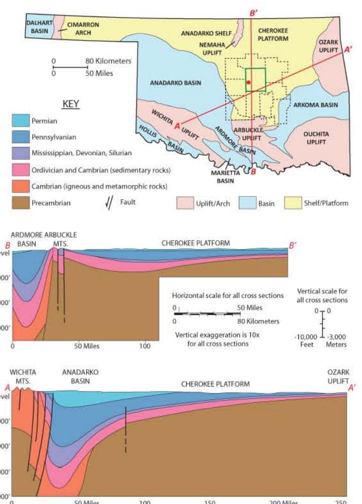


Figure 5: Major geologic provinces of OK. Core location (red dot) in Lincoln County (outlined green) is at the intersection of the two cross sections (modified from OGS, 2008).

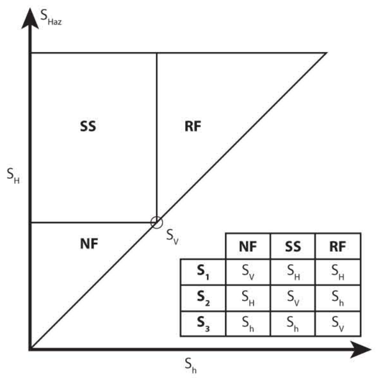
Previous Work

The prediction of wellbore stability or the investigation of the reservoir and overburden compaction behavior during reservoir depletion are examples of the complex problems requiring a thorough knowledge of the formations anisotropic 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 side effects include:

- Triaxial tests; coring is expensive and time-consuming, data is sparse and hard to access, post-recovery relaxation and alteration of cores can bias data (Woehrl et al., 2010).
- Formation evaluation logs; an interpretive approach, allows for calculating a continuous succession of mechanical properties over a large depth interval (Work, 1975; Fertl, 1990).

Approach

Rocks can fail under confinement when all stresses acting on the rock are positive, as long as the differential stress ($S_1 - S_3$) exceeds the strength of the material. When rocks are forced to fail under zero confinement, the pressure at which failure occurs is called the Unconfined Compressive Strength (UCS), herein measured in psi (Enderlin and Alsleben, in press). In this study, UCS values are determined using a handheld point-load penetrometer (referred to as the Dimpler) 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 directions of the present-day stresses that confine 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 (Enderlin and Alsleben, 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 (Moos and Zoback, 1990).



	NF	SS	RF
S_1	S_V	S_H	S_H
S_2	S_H	S_V	S_h
S_3	S_h	S_h	S_V

Figure 6: Generic Stress Polygon showing the relationship between the three component stresses (S_V, S_H, and S_h) that make up the current stress state (S) of a region, and the principal stresses (S_1, S_2, and S_3) within the normal fault (NF), strike-slip fault (SS), and reverse fault (RF) stress domains as defined by Anderson (1951). The magnitude of S_V, which varies by location, plots along the equality line and constrains the stress domain dimensions (modified after Moos and Zoback, 1990).

Core

Whole core extracted from the Woodford Shale at the EOG Smith, B. #31-3 SWD and stored at the Oklahoma Petroleum Information Center (OPIC) is the focal point of this study (Figure 7). The coring interval extends from a depth of 5198' (feet) to 5260' measured depth (MD), penetrating 61' of the lower Woodford and one foot of the underlying Hunton Formation. The yellow bar positioned on the core photos just above sample location #6 represents the contact between the Woodfrod Shale and the Hunton Formation (limestone). This contact was the marker used to depth-register the core on the logs.

Depth Interval: 5160' - 5269'
Gamma Ray Log

Depth Interval: 5254' - 5260'
(Wet) (Dry)

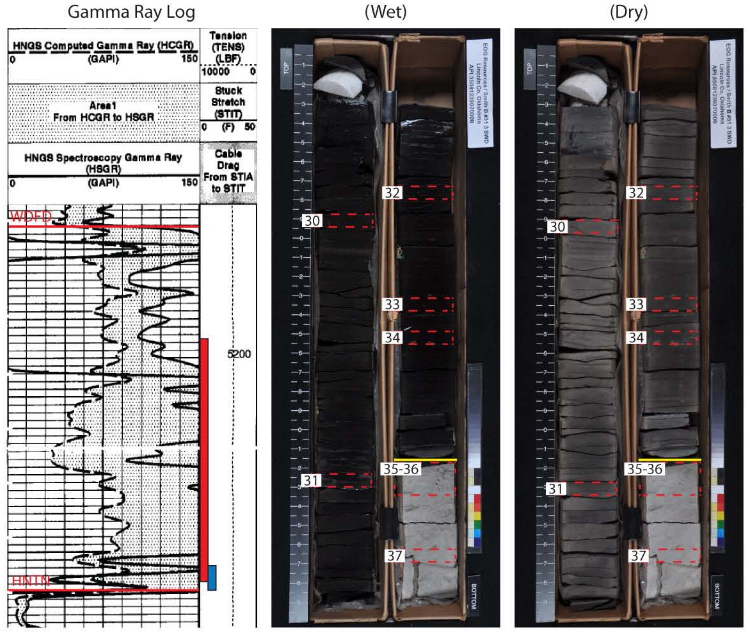


Figure 7: Gamma ray well log from the EOG Smith, B. #31-3 SWD well. Color annotations include Woodford Shale and Hunton Formation tops (red lines), total cored interval (red box in the depth track), depth interval of the adjacent a set of sample core photographs (blue box in the depth track). Whole core photographs (wet and dry samples) of the base of the Woodford Shale from the EOG Smith, B. #31-3 SWD. Dashed red boxes represent the sample depths at which this interval of core was strength tested. The distinct lithologic change in the core photographs (yellow line) is the contact between the Woodford Shale (medium gray color) and the underlying Hunton Formation (light gray limestone). Photographs and well log courtesy of OPIC, 2012.

Determining 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 conical point is coated in red ink and then pressed at a constant axial load perpendicular to a one-square-inch-size piece of removable tape that has been placed atop the surface of interest (Figure 8; Ramos et al., 2008).

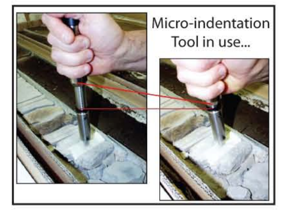


Figure 8: Dimples are made in clusters of four or five at regular intervals over the length of the core to acquire a statistically significant sample size (modified from Enderlin and Alsleben, in press).

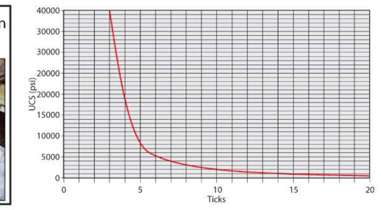


Figure 9: Graphic correlation between the diameter of a dimple created by the micro-indentation tool and the UCS of the sample in psi. Dimple size is measured in "ticks" (each tick being equal to 0.005 of an inch) (modified from Enderlin, in press).

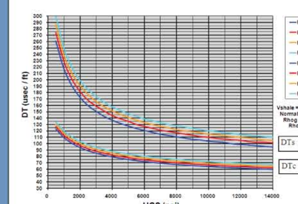


Figure 10: Correlation between UCS and DT (usec/ft) for normally pressured, quartz-rich, brine-filled sandstones (modified from Weingarten and Perkins, 1995).

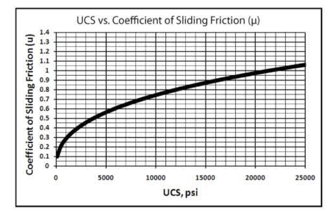


Figure 11: Correlation between Coefficient of Sliding Friction (μ) and UCS. For most rocks, Byerlee (1978) estimates μ ~ 0.85, Zoback (2007) μ ~ 0.6 (modified from Enderlin, in press).

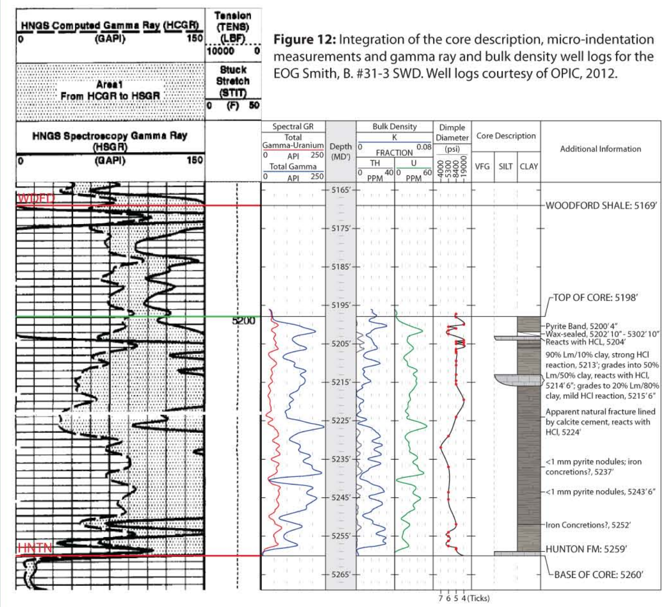


Figure 12: Integration of the core description, micro-indentation measurements and gamma ray and bulk density well logs for the EOG Smith, B. #31-3 SWD. Well logs courtesy of OPIC, 2012.

Earthquakes

On November 6th, 2011, a magnitude 5.6 earthquake (the largest recorded in Oklahoma) ruptured in southeast Lincoln County, 21 miles southeast of the EOG Smith, B. #31-3 SWD core location. The source appears to be a currently unnamed, basement-seated, right-lateral strike-slip fault (strike ~57°) (Holland (2012). Although the fault is still being mapped, it is considered to be a major splay of the Wilzetta fault (strike ~27°) (Table 1; Figures 13 and 14; Joseph, 1987; Gay, 2003).

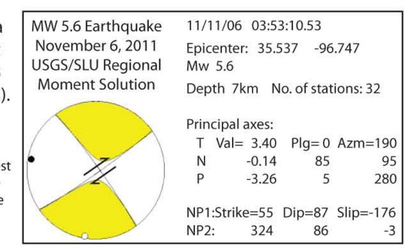


Figure 13: Focal mechanism for the largest earthquake. Data from Table 1 and Figure 14 indicate that Nodal Plane 1 (NP1) is the fault plane and NP2 the auxiliary plane. Adapted from USGS, 2011.

Table 1: List of magnitude 4.0+ earthquakes in Lincoln County, OK since the completion of the EOG Smith, B. 31 #3 SWD (USGS, 2011).

Event	Date	Location	Depth
EOG Smith, B. 31 #3 SWD	2-22-2007	31 – T14N – R2E	1.87 km (6132 ft TD)
Magnitude 4.0 Earthquake	1-15-2010	35.537°N, 96.747°W; 11 – T12N – R5E	5 km (3.1 miles)
Magnitude 4.1 Earthquake	2-27-2010		3 km (1.9 miles)
Magnitude 4.3 Earthquake	10-13-2010		13 km (8.1 miles)
Magnitude 4.7 Foreshock	11-5-2011		4 km (2.5 miles)
Magnitude 5.6 Earthquake	11-6-2011		5 km (3.1 miles)
Magnitude 4.7 Aftershock	11-8-2011		5 km (3.1 miles)

Establishing the Stress State

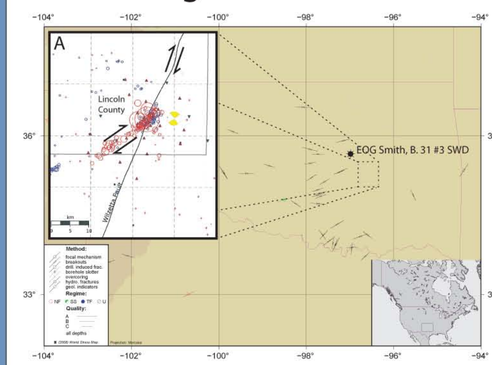
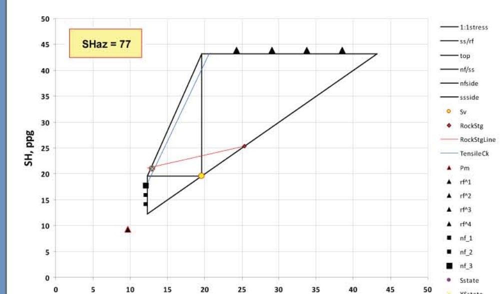


Figure 14: E-W oriented borehole breakout data from the World Stress Map (shown as ⟶ on the basemap) indicate that the orientation of S_{Haz} is ~87°. The historical seismicity of southwestern Lincoln County confirms this estimate (inset map A), showing earthquakes from 1/1/2010 to 11/4/2011 (blue circles) and 1/5/2011 (red circles) mapped as circles by size relative to their magnitude. These data provide strong evidence for a right-lateral strike-slip fault striking ~57°, dipping 80-85° east (Heidbach et al., 2008; Holland, 2012).



	12.3	Fault Marker Off = 0			1		Strength Marker Off = 0		1
Depth, ft, tvd	Sv	CSF	SH	Sh	Pp	Pm	UCS, ppg	IFA, deg.	Cohesion, psi
4256	19.6	0.62	21	13	9	9.7	27.6	47	204
	4333 psi	0.61	4643 psi	2874 psi	1990 psi	2145 psi	6102	47	1202
			SHaz, deg.	Borehole Stresses		0.7	6102	36.9	204
			77	SH side	Sh side	154.8	1036	47	204
			283	-1 ppg	31 ppg		5	= ppg =	0.9
				-155	6920	ang. to S1 =22	7099 psi	32.1 ppg	= CCS

Figure 15: Interactive Stress Polygon built in Microsoft Excel (2008) produces a unique result based on data inputs, integrating the component stresses S_H and S_h with the coefficient of sliding friction (CSF), pore pressure, mud weight, Unconfined Compressive Strength (UCS), Internal Friction Angle (IFA) and cohesion (modified from Enderlin and Alsleben, in press).

Using the stress magnitudes and rock strength values for the Woodford Shale at the EOG Smith, B. #31-3 SWD well location (Figure 15), it is anticipated that vertical fractures oriented 30° from S_{Haz} (~77°) can be reactivated if the pressure sources exceed a UCS ~ 7200 psi.

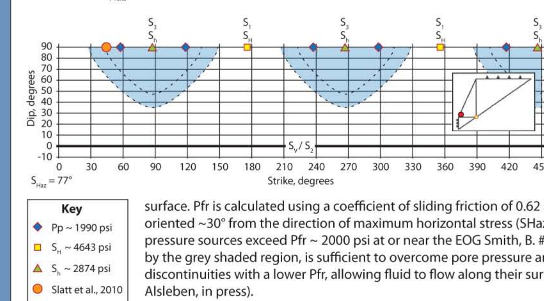


Figure 16: Given that Sv = 4333 psi (29.9 MPa), SH = 4643 psi (32.0 MPa), and Sh = 2874 psi (19.8 MPa), a reactivation map for the study area illustrates the reactivation pressure (Pfr in psi) required with any paired strike-dip combination in order to activate movement on that surface. Pfr is calculated using a coefficient of sliding friction of 0.62 and zero cohesion. Vertical fractures oriented ~30° from the direction of maximum horizontal stress (SHaz ~ 077°) can be reactivated if the pressure sources exceed Pfr ~ 2000 psi at or near the EOG Smith, B. #31-3 SWD. This pressure, illustrated by the grey shaded region, is sufficient to overcome pore pressure and re-open preexisting mechanical discontinuities with a lower Pfr, allowing fluid to flow along their surfaces (modified from Enderlin and Alsleben, in press).

Conclusions

1. Characterization of the Woodford Shale rock strength from core and well logs collected from the EOG Smith, B. 31 #3 SWD well on the Cherokee Platform, Lincoln County, OK indicates that vertical fractures oriented 30° from S_{Haz} (~77°) can be reactivated if the pressure sources exceed a UCS ~ 2000 psi, allowing fluid flow along their surfaces.
2. Various combinations of strikes and dips with Pfr values (in psi) between pore pressure (~1990 psi) and Sh (~ 2874 psi) are likely to be reactivated in the current stress state.
3. The micro-indentation method presented makes it possible to cost-effectively assess the fracture reactivation potential of a formation in both field and laboratory settings.
4. Analysis of the contemporary stress state incorporating earthquake focal mechanisms, mapped active faults and historical data from the World Stress Map provide evidence for an active domain of right-lateral strike-slip faulting in Central Oklahoma.
5. As presented herein, a combined stress/strength approach illustrates the relationship between the reactivation of natural fractures and the hydraulic fracture stimulation of low porosity, low permeability reservoirs.

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