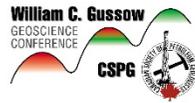


# New Directions in Geosciences for Unconventional Resources

**OCTOBER 15-17, 2019**

BANFF, CANADA



## State of Stress in North American Unconventional Oil and Gas Producing Basins

Jens-Erik Lund Snee<sup>1</sup>, Mark D. Zoback<sup>\*1</sup>; 1. Department of Geophysics, Stanford University

### Abstract

The state of stress directly influences several key aspects of unconventional oil and gas development, including both the ideal orientation for drilling horizontal wells and the effectiveness of hydraulic fracturing stimulations. Over the past several years, the Stanford Stress Group has collected more than 600 new maximum horizontal principal stress ( $S_{Hmax}$ ) orientations across North America as well as 1900 hundred estimates of the relative magnitude of the three principal stresses utilizing earthquake focal plane mechanisms. In this presentation, we will discuss these “new generation” stress maps, paying particular attention to the stress state in major unconventional oil- and gas-producing basins.

### Statement of the background

Development of unconventional oil and gas reservoirs utilizing horizontal drilling and multi-stage hydraulic fracturing is a geomechanical process. Thus, knowledge of the orientation and relative magnitude of principal stresses is of fundamental importance. Horizontal wells are optimally productive when they are drilled in the direction of the minimum horizontal stress ( $S_{Hmin}$ ). Relative stress magnitudes affect the pressure require to initiate and extend hydraulic fractures as well as the initiation of slip on pre-existing fractures and faults in the rock mass surrounding the hydraulic fractures.

### Aims and Objectives

This presentation represents a new generation of stress maps to guide development of unconventional reservoirs using horizontal drilling and multi-stage hydraulic fracturing. In many areas of unconventional development, the direction of the horizontal principal stresses is quite consistent, making it relatively easy to drill in the optimal direction parallel to that of  $S_{Hmin}$ . In other areas, systematic variations of horizontal stress directions occur (perhaps best exemplified in the Delaware Basin), which makes it important to lay out well trajectories carefully. In several cases, particularly areas generally in the Rocky Mountains, there appear to be rapid changes in principal stress directions over relatively short distances. Relative stress magnitudes control the way in which slip is stimulated on pre-existing fracture and fault planes, and they affect the magnitude of the least principal stress, which defines the pressure needed to propagate a hydraulic fracture. Knowledge of stress orientation and magnitude is essential information for avoiding faults that might be susceptible to injection-induced seismicity (e.g., Walsh and Zoback, 2016; Lund Snee and Zoback, 2016, 2018).

## Materials and methods

This work builds upon 40 years of efforts to map stress orientation and relative magnitudes in the Earth's crust (Zoback and Zoback, 1980; Zoback, 1992). While many of the methods to map crustal stresses are well established (see review in Zoback, 2007), several new sources of data are now available. These include using the trend of linear microseismic clouds associated with multi-stage hydraulic fracturing (see Zoback and Kohli, 2019) and hydraulic fractures observed in recently-drilled horizontal wells that were generated in vertical wells previously drilled in the area. In addition to hundreds of new wellbore-related  $S_{Hmax}$  orientation, numerous new earthquake focal plane mechanisms are available, which provide constraints for the relative stress magnitudes. When a sufficient number of well-constrained focal plane mechanisms are available in a localized area, these can be inverted to precisely calculate the relative stress magnitudes (e.g., Michael, 1984, 1987; Vavryčuk, 2014).

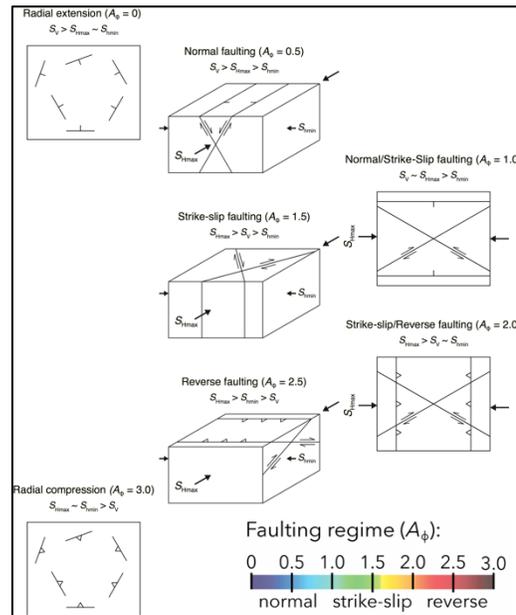


Figure 1: Extended Andersonian faulting theory (Anderson, 1951) to incorporate intermediate and limiting stress states (see text). We assign a numerical value to each stress state following Simpson (1997). The color scale shown is used as the background color in the stress maps in Figures 1, 3 and 4. After Lund Snee and Zoback (2018)

To represent the relative magnitudes of the three principal stresses ( $S_V$ ,  $S_{Hmax}$ , and  $S_{hmin}$ ) on maps, we use the  $A_\square$  parameter defined by Simpson (1997), which conveniently describes the ratio between the principal stress magnitudes using a single, readily interpolated value that ranges smoothly from 0 (the most extensional possible stress state) to 3 (the most compressive).  $A_\square$  values correspond to the seven general stress states is shown in Figure 1. The parameter is defined mathematically by

$$A_\phi = (n + 0.5) + (-1)^n(\phi - 0.5),$$

where

$$\phi = \frac{S_2 - S_3}{S_1 - S_3}.$$

$S_1$ ,  $S_2$ , and  $S_3$  are the magnitudes of the maximum, intermediate, and minimum principal stresses, respectively, and  $n$  is 0 for normal faulting ( $S_V = S_1$ ,  $S_{Hmax} = S_2$  and  $S_{hmin} = S_3$ ), 1 for strike-slip faulting ( $S_V = S_2$ ,  $S_{Hmax} = S_1$  and  $S_{hmin} = S_3$ ) and 2 for reverse faulting ( $S_V = S_3$ ,  $S_{Hmax} = S_1$  and  $S_{hmin} = S_3$ ). The  $A_\square$  values that correspond to the seven stress states described above are shown in Figure 1, as well as the

color scale used in the stress maps. Note that  $A_1$  varies smoothly between each of the stress states shown as the ratio between the three principal stresses changes.

## Results and discussion

Figure 2 (from Lund Snee and Zoback, 2019a) shows the orientation of  $S_{Hmax}$  as well as the relative magnitudes of the principal stresses. The length of each stress indicator is a measure of the quality of each measurement using the updated quality criterion summarized in Zoback and Kohli (2019). Quality criteria were first widely used for the stress compilation in the World Stress Map project (M.L. Zoback, 1992).

The background color in the map indicates relative stress magnitude using the methodology of Simpson (1997). The meaning of the  $A_1$  parameter is illustrated in Figure 1. Earthquake focal plane mechanisms were used to constrain relative stress magnitude. As indicated by the color bar in the legend, large regions of consistent relative stress magnitudes are seen, as first pointed out by Zoback and Zoback (1980). The question marks on the map indicate where there are few focal mechanisms available such that interpolation of available data is uncertain. See Lund Snee and Zoback (2019a) for a thorough explanation of the data used in the map and the associated uncertainties.

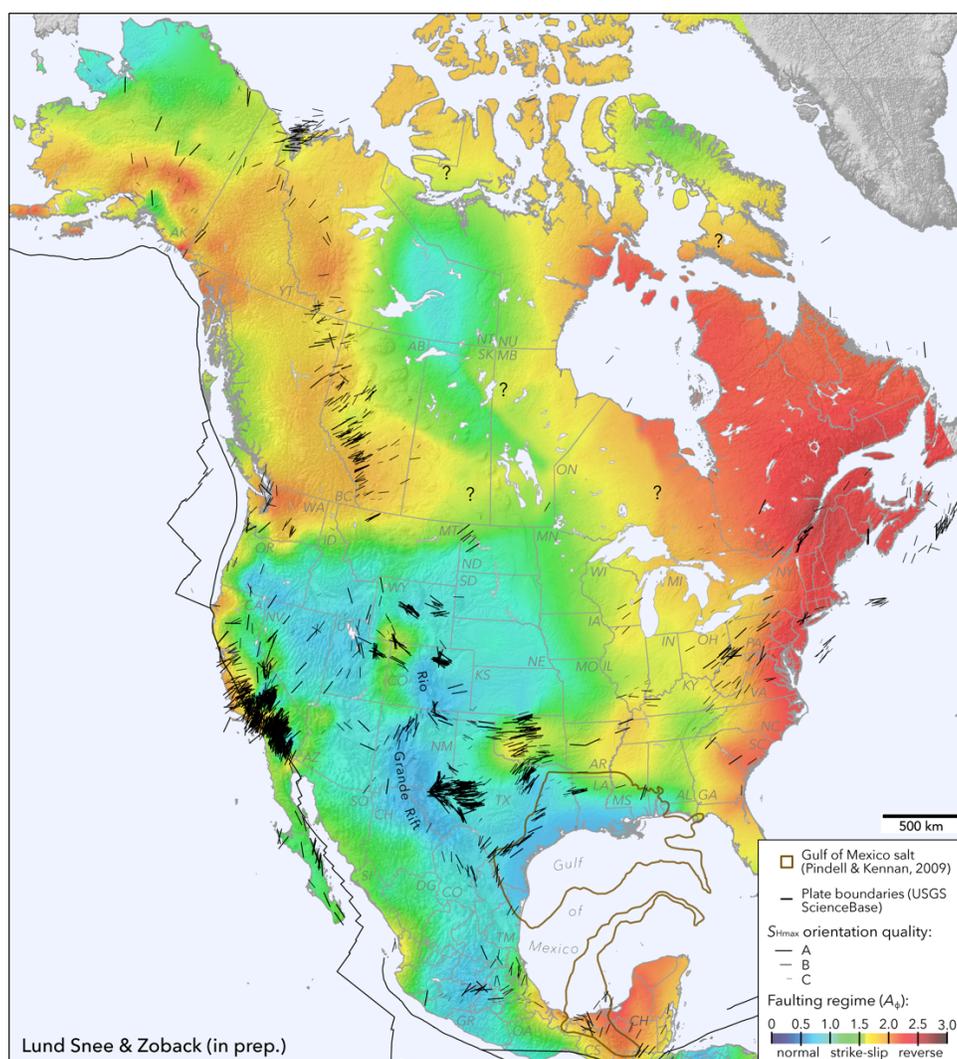


Figure 2: Map of the direction of maximum horizontal stress and relative stress magnitude throughout North America (from Lund Snee and Zoback, 2019a). Detailed maps are presented in subsequent figures. The background color represents relative stress magnitudes as defined by the  $A_1$  parameter of Simpson (1997) and illustrated in Figure 1.

Figure 3 shows stress orientations and relative magnitudes in Oklahoma and the northeastern U.S. North-central Oklahoma, where there have been numerous earthquakes triggered by produced water injection (Walsh and Zoback, 2015), is characterized by relatively uniform  $\sim N085^{\circ}E$  direction of  $S_{Hmax}$  (Alt and Zoback, 2017). This area is characterized by strike-slip faulting that gradually changes to a strike-slip/normal faulting near the Kansas/Oklahoma border. The stress direction rotates counter clockwise in southwest Oklahoma (in the area of SCOOP AND STACK unconventional development in the southeastern Anadarko Basin) and continues rotating counter clockwise into the northern part of the Fort Worth Basin (Lund Snee and Zoback, 2016; Hennings et al., 2019).

The state of stress in the northeastern U.S. in the area of Utica and Marcellus unconventional development is characterized by a consistent ENE–WSW  $S_{Hmax}$  direction and an increasingly compressional stress state northeastward (Zoback and Zoback, 1980; Hurd and Zoback, 2012). In fact, in northern West Virginia, easternmost Ohio and much of Pennsylvania, there is a strike-slip/reverse faulting stress state ( $S_{Hmin} \approx S_V < S_{Hmax}$ ). As shown by Alalli and Zoback (2018), this leads to the propagation of horizontal hydraulic fracture initiation in some areas.

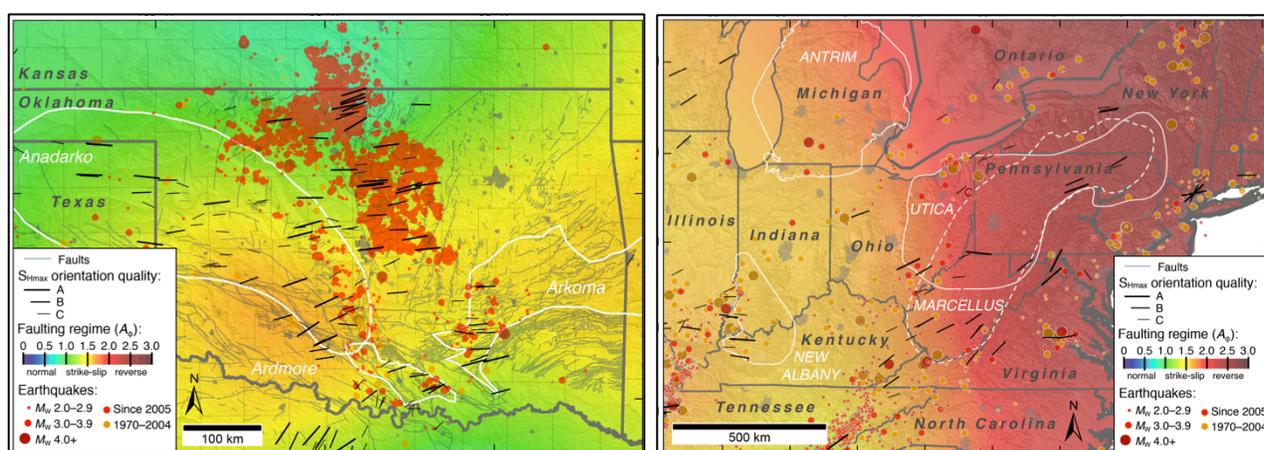


Figure 3: (Left) The orientation of maximum horizontal principal stress ( $S_{Hmax}$ ) and relative stress magnitudes in Oklahoma, as well as the location of earthquakes (see legend), most of which were induced by injection of produced water (see text). (Right) The orientation of  $S_{Hmax}$  in the northeastern U.S. as well as earthquakes in the area. From Lund Snee and Zoback (2019b).

Figure 4 shows the orientations of  $S_{Hmax}$  and relative stress magnitudes in the Fort Worth Basin (upper left), the Permian Basin (lower left) and Western Canadian Sedimentary Basin (WCSB, right). The state of stress in the Fort Worth Basin is characterized by NE–SW compression and a normal/strike-slip faulting regime ( $S_{Hmin} < S_{Hmax} \approx S_V$ ). Many early workers argued that the Fort Worth Basin was characterized by sub-equal horizontal stresses, which we now know to be incorrect, as illustrated in Figure 4. The stress state in the Midland Basin and Central Basin Platform portions of the Permian Basin is characterized by relatively uniform  $\sim E$ – $W$  compression and a strike-slip/normal faulting regime. The Delaware Basin is characterized by normal faulting and a dramatic north to south clockwise rotation of  $S_{Hmax}$  from N–S in southeast New Mexico, to E–W near the border of New Mexico and Texas, to NW–SE in the southern Delaware Basin. The Permian Basin stress state is discussed thoroughly by Lund Snee and Zoback (2018). Finally, as shown in the map on the right side of the figure, the state of stress in the WCSB is characterized by  $\sim N045^{\circ}E$  compression and a strike-slip faulting stress state. In central Alberta, a number of stress orientation measurements show a more northerly  $S_{Hmax}$  direction (NNE of Fox Cree, indicated by the red star). In other parts of Alberta slight variations of the  $S_{Hmax}$  direction are observed but overall, it appears to be a remarkably uniform stress field.

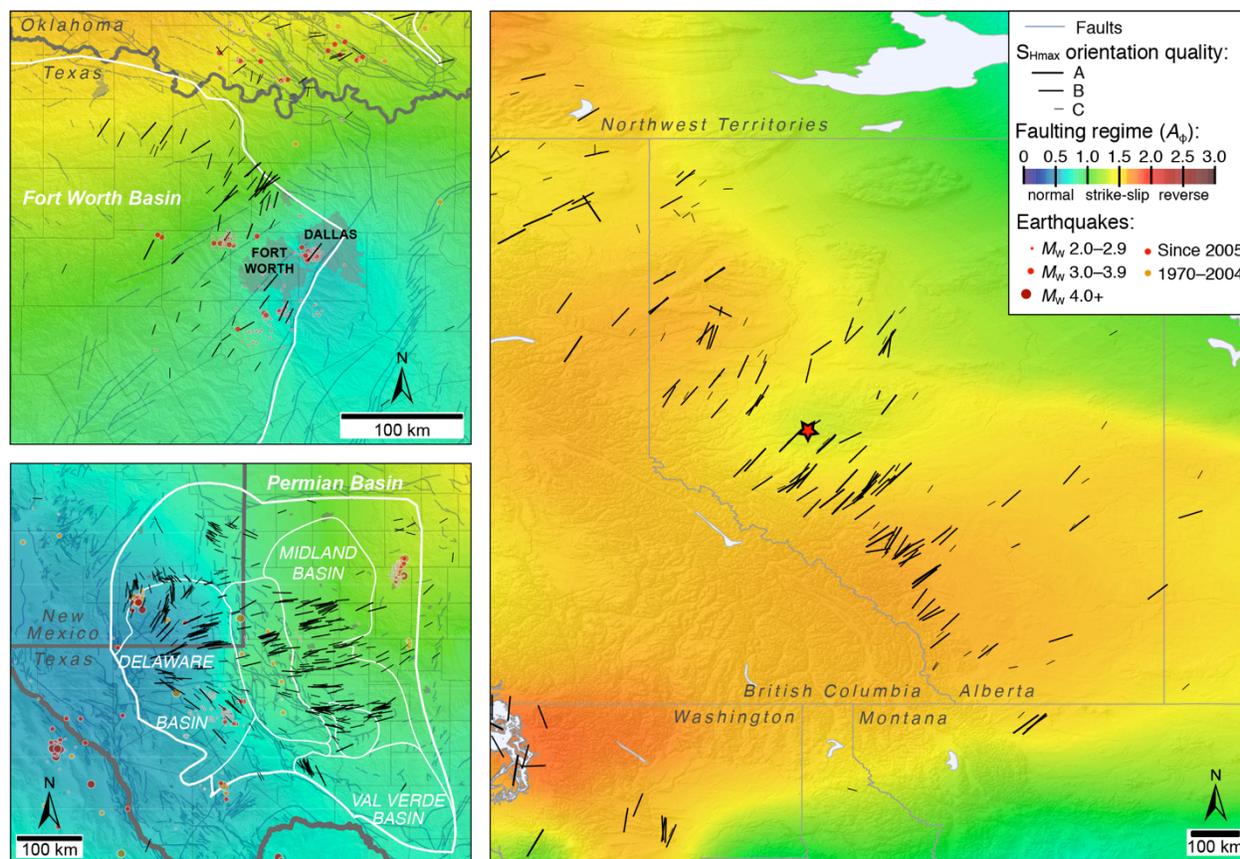


Figure 4: The orientation of  $S_{Hmax}$  and the relative stress magnitudes in the Fort Worth Basin (upper left, from Lund Snee and Zoback, 2016, 2019b, and Hennings et al., 2019), the Permian Basin (lower left, after Lund Snee and Zoback, 2018) and the Western Canadian Sedimentary Basin (right, from Lund Snee and Zoback, 2019b). The red star indicates the Fox Creek area.

While the implications of the maps above for drilling wells in the direction of the minimum horizontal stress are obvious, the more subtle importance is the impact of stress orientation and relative magnitude on the way in which shear slip is triggered on pre-existing faults and, potentially, on sub-horizontal bedding planes during multi-stage horizontal fracturing. This is illustrated in Figure 5 using both Mohr circles and stereonets (from Zoback and Lund Snee, 2018). The figure contrasts the subset of natural fracture orientations that can be made to slip in response to high fluid pressures injected during hydraulic fracturing operations under normal/strike-slip faulting (upper diagram) and reverse/strike-slip faulting (lower diagram) stress states. As discussed in detail by Hakso and Zoback (2019) and Zoback and Kohli (2019) the shear stimulation process is critical to the success of hydraulic fracturing. Zoback and Lund Snee (2018) discuss the importance of the stress state for controlling which orientations of poorly-oriented natural fractures can be made to slip during hydraulic stimulation, and which cannot. They also point out that slip (or opening) along bedding planes is impossible in extensional and strike-slip faulting environments, but that it could occur in compressional (reverse and reverse/strike-slip faulting) environments. This comparison is shown by the Mohr circles on the left side of Figure 5.

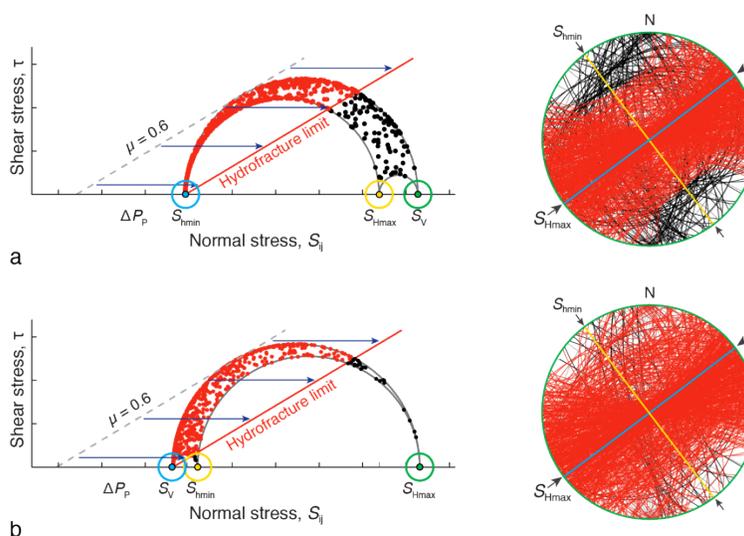


Figure 5: Evaluation of the tendency for shear slip or opening on planes normal to one of the principal stresses. Sub-horizontal bedding planes are illustrated by the green dot on Mohr diagram (left) and the planes shown in green on the stereonet (right). Planes normal to  $S_{\text{hmin}}$  (sub-parallel to hydraulic fractures) are indicated in blue, and those normal to  $S_{\text{Hmax}}$  are indicated in yellow. a) A normal/strike-slip faulting stress state ( $S_{\text{hmin}} \ll S_{\text{Hmax}} \sim S_{\text{V}}$ ). b) A strike-slip/reverse faulting stress state ( $S_{\text{hmin}} \sim S_{\text{V}} \ll S_{\text{Hmax}}$ ). Modified from Zoback and Lund Snee (2018).

## Conclusions

Principal horizontal stress directions and relative stress magnitudes are presented for a number of areas where unconventional oil and gas are being developed in North America. Systematic stress variations are observed at a number of scales. Comprehensive mapping of the stress field has considerable value in optimizing the development of these resources and avoiding the occurrence of injection-related seismicity.

## References

- Alalli, A. A., & Zoback, M. D. (2018). Microseismic evidence for horizontal hydraulic fractures in the Marcellus Shale, southeastern West Virginia. *Leading Edge*, 37(5). <https://doi.org/10.1190/tle37050356.1>
- Alt, R. C. & Zoback, M. D. (2017). In situ stress and active faulting in Oklahoma. *Bulletin of the Seismol. Soc. of America*, 107(1), 1–13. <https://doi.org/10.1785/0120160156>
- Hakso, A., & Zoback, M. D. (2019). The Relation Between Stimulated Shear Fractures and Production in the Barnett Shale: Implications for Unconventional Oil and Gas Reservoirs. *Geophysics, in review*.
- Hennings, P. H., Lund Snee, J.-E., Osmond, J. L., DeShon, H. R., Dommissie, R., Horne, E., et al. (2019). Injection-induced seismicity and fault slip potential in the Fort Worth Basin, Texas. *Bulletin of the Seismological Society of America*.
- Hurd, O. & Zoback, M. D. (2012). Intraplate earthquakes, regional stress and fault mechanics in the central and eastern U.S. and Southeastern Canada. *Tectonophysics*, 581. <https://doi.org/10.1016/j.tecto.2012.04.002>
- Lund Snee, J.-E. and Zoback, M. D. (2016). State of stress in Texas: Implications for induced seismicity. *Geophysical Research Letters*, 43(19), 10,208–10,214. <https://doi.org/10.1002/2016GL070974>
- Lund Snee, J.-E. and Zoback, M. D. (2018). State of stress in the Permian Basin, Texas and New Mexico: Implications for induced seismicity. *The Leading Edge, February*. <https://doi.org/10.1190/tle37020127.1>

Lund Snee, J.-E. and M.D. Zoback (2019a) Stress orientation and relative magnitudes throughout North America, *Jour. Geophys. Res.*, in preparation.

Lund Snee, J.-E. and M.D. Zoback (2019b) Stress orientation and relative magnitudes in unconventional oil and gas reservoirs in North America, *Amer. Assoc. Petrol. Geol. Bull.*, in preparation.

Michael, A. J. (1984). Determination of stress from slip data: Faults and folds. *Journal of Geophysical Research*, 89(B13), 11517. <https://doi.org/10.1029/JB089iB13p11517>

Michael, A. J. (1987). Use of focal mechanisms to determine stress: A control study. *Journal of Geophysical Research*, 92(B1), 357–368. <https://doi.org/10.1029/JB092iB01p00357>

Simpson, R. W. (1997). Quantifying Anderson's fault types, *Jour. Geophys. Res.* 102, 909–919.

Vavryčuk, V. (2014). Iterative joint inversion for stress and fault orientations from focal mechanisms. *Geophysical Journal International*, 199(1), 69–77. <https://doi.org/10.1093/gji/ggu224>

Walsh, F. R. and Zoback, M. D. (2015). Oklahoma's recent earthquakes and saltwater disposal. *Science Advances*, 1(5). <https://doi.org/10.1126/sciadv.1500195>

Walsh, F. R. and Zoback, M. D. (2016). Probabilistic assessment of potential fault slip related to injection-induced earthquakes: Application to north-central Oklahoma, USA. *Geology*, 44(12), 991–994. <https://doi.org/10.1130/G38275.1>

Zoback, M. D. (2007). *Reservoir Geomechanics*. Cambridge, England: Cambridge University.

Zoback, M. D. and A. H. Kohli (2019). *Unconventional Reservoir Geomechanics*. Cambridge, England: Cambridge University.

Zoback, M. D. and Lund Snee, J.-E. (2018). Predicted and observed shear on pre-existing faults during hydraulic fracture stimulation. In SEG Technical Program Expanded Abstracts. Society of Exploration Geophysicists.

Zoback, M. L. and Zoback, M. D. (1980). State of stress in the conterminous United States. *J. Geophys. Res.*, 85, 6113–6156.

Zoback, M. L. (1992). First and second order patterns of tectonic stress: The World Stress Map Project. *Journal of Geophysical Research*, 97, 11,703-711,728.