

WSM presentation at the AGU 2017

by Oliver Heidbach (GFZ Potsdam)

At the AGU 2017 in New Orleans Natalia Zakharova from the Columbia University (USA) and her colleagues Chandong Chang from the Chungnam National University (Republic of Korea) and Hiroki Sone from GFZ Potsdam (Germany) organized the session T14C entitiled „In Situ Stress Field: Observations, Uncertainties, and Modeling“.

The poster session with authors in attendance is on Monday 11th from 8:00 AM onwards in Hall D-F with the poster numbers T11B-0454 through T11B-0470. The oral session is in Monday 11th in the afternoon from 16:00-18:00 in room 231-232. Here we present at 16:00 the key findings of the new World Stress Map Release 2016, but if you want to meet us - Karsten Reiter from the WSM Team is also at the conference - you can find us at our posters T11B-0460 „Stress rotation along pre-Cenozoic basement structures“ and T11B-0468 „From point-wise stress data to a continuous description of the 3D crustal in situ stress state“.

The WSM newsletter reaches currently more than 3,000 subscribers from academia and industry. You are invited to contribute to the WSM newsletter to announce your key research results, opinions or comments with short articles. The editorial deadline for the next newsletter to be send in early April 2018 is March 30th 2018. We wish you a merry X-mas season and all the best for the year 2018.

The WSM Team

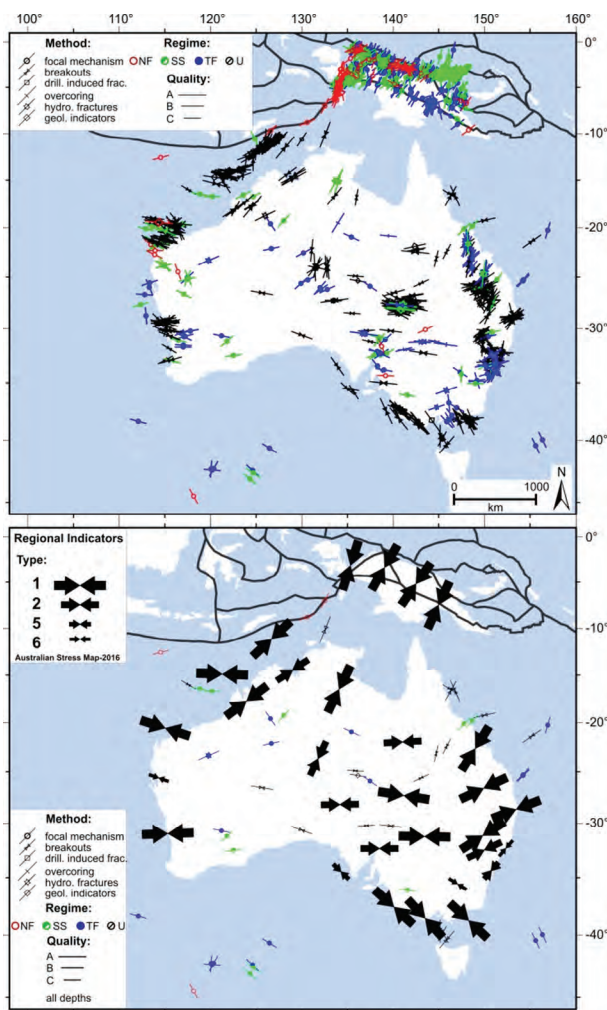
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French Quarter in New Orleans, USA

The AGU 2017 is this year in New Orleans from December 11th-15th.

The present-day stress pattern of the Australian continent has been the subject of scientific debate for over 25 years. Despite the extensive and widespread stress analysis undertaken in the early phases of the Australian Stress Map (ASM) project, the stress field for many parts of Australia, and particularly eastern Australia, remained poorly resolved, with the dataset primarily comprised of shallow engineering test data and predictions based on numerous geomechanical-numerical models. In the past five years we analysed and compiled an extensive new stress dataset across the Australian continent. The result of this study has been recently published as an 'invited review paper' in *Earth-Science Reviews* (Rajabi et al., 2017a). This study presents the new release of the ASM project, with a total of 2150 stress data records in Australia (increased from 594 data records in 2003). The 2016 ASM contains 1359 data records determined from the interpretation of drilling-related stress indicators, 650 from earthquake focal mechanism solutions, 139 from shallow engineering measurements and two from geological indicators.



The new compilation of the ASM highlights the inability of all prior geomechanical-numerical models to reliably predict the stress pattern in eastern Australia (Rajabi et al., 2017a, b). In this study, the regional stress field in Australia is described and interpolated using various statistical methods that reveals four major trends for the orientation of maximum horizontal stress (S_{Hmax}) in the Australian continent, including a NNE-SSW S_{Hmax} trend in northern and northwestern Australia, which rotates to a prevailing E-W orientation in most Western and South Australia. The orientation of S_{Hmax} in eastern Australia is primarily ENE-WSW and swings to NW-SE in southeastern Australia.

In addition to this regional variability, high density data sets in sedimentary basins of eastern Australia revealed stress perturbations at smaller scales due to different geological features such as basement structures, fractures, faults and lithological contrasts (see Rajabi et al., 2016, Rajabi et al., 2017a, b, c). In addition to the S_{Hmax} orientation, the analysis of tectonic stress regimes, based on 211 data records, in onshore Australia suggests that a thrust faulting stress regime predominantly exists in the upper two km of the Australian continental crust. Furthermore, the database indicates that the stress regime changes in deeper parts of the crust, where a strike-slip stress regime is prevailing.

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Stress Map Australia

Map shows stress data records (above) and the mean orientation of maximum horizontal stress (S_{Hmax}) within 30 stress provinces in Australia. Colours indicate different stress regimes (SS: strike-slip, NF: normal, TF: thrust and U: undefined tectonic stress regimes). The azimuth of each line shows the S_{Hmax} orientation and line length indicates data quality.

Key References

- Rajabi, M., Tingay, M., Heidbach, O., Hillis, R., Reynolds, S., 2017a. The present-day stress field of Australia. *Earth-Science Rev* 168, 165-189. <http://doi.org/10.1016/j.earscirev.2017.04.003>.
- Rajabi, M., Tingay, M., Heidbach, O., 2016. The present-day stress field of New South Wales, Australia. *Australian Journal of Earth Sciences* 63, 1-21. <https://doi.org/10.1080/08120099.2016.1135821>

Detailed new map of S_{Hmax} orientations and relative stress magnitudes in the south-central USA

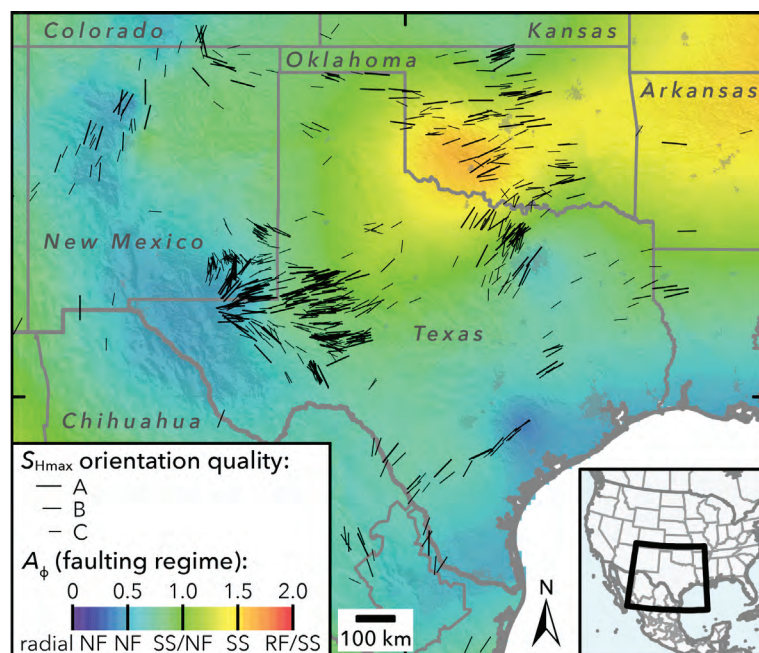
by Jens-Erik Lund Sneek and Mark D. Zoback (Stanford University)

We have collected over 400 new orientations of the maximum horizontal stress (S_{Hmax}) and mapped the faulting regime (relative principal stress magnitudes) across Texas, New Mexico, Oklahoma, and surrounding areas. The new data, published in studies by Alt and Zoback (2017) and Lund Sneek and Zoback (2016, 2018), reveal a remarkably coherent but regionally variable stress field.

In much of the central and eastern USA, and parts of southern and eastern Canada, S_{Hmax} is oriented ENE–WSW to NE–SW, and the stress field is compressive (reverse and strike-slip faulting), consistent with compression ridge push from the Mid-Atlantic Ridge (M.L. Zoback, 1992; Hurd and Zoback, 2012). The stress field becomes increasingly extensional westward, with strike-slip faulting in central Oklahoma and both strike-slip and normal faulting in northernmost Oklahoma and southern Kansas. S_{Hmax} is oriented \sim ENE–WSW. Southwest Oklahoma is compressive, with a strike-slip/reverse faulting stress state, but the stress state becomes increasingly extensional southward and westward from there, and S_{Hmax} orientations rotate to nearly N–S in northeast Texas, where the faulting regime is normal/strike-slip.

Progressing westward, S_{Hmax} rotates clockwise to again become \sim E–W, but dramatic rotations are observed in the Delaware Basin of west Texas and southeastern New Mexico moving westward to the \sim N–S orientations observed along the extensional Rio Grande Rift in central New Mexico and westernmost Texas. Further north, in southeast Colorado and northeast New Mexico, a similarly sharp rotation from \sim E–W to \sim N–S is observed moving westward from the Raton Basin into the Rio Grande Rift. Along the Gulf Coast, to the southeast, S_{Hmax} is subparallel to the coastline and the faulting regime is mostly normal faulting in the sedimentary column, although it is normal/strike-slip faulting in southwest Texas and easternmost Mexico. We are applying these new stress data to studies of active tectonics, induced seismicity, and oil and gas productivity.

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Stress Map South-Central USA

Map of S_{Hmax} orientations (black lines) and relative stress magnitudes (colored background) depicted using the A_ϕ parameter defined by Simpson (1997). S_{Hmax} orientations are from Lund Sneek and Zoback (2016, 2018), Alt and Zoback (2017), and Heidbach et al. (2016). NF—normal faulting, SS—strike-slip faulting; RF—reverse faulting.

Key References

- Alt, R.C., II, and Zoback, M.D. 2017. In situ stress and active faulting in Oklahoma. *Bulletin of the Seismological Society of America*, 107(1): 216–228, doi:10.1785/0120160156.
- Lund Sneek, J.-E., Zoback, M.D. 2016. State of stress in Texas: Implications for induced seismicity. *Geophysical Research Letters*, 43: 10,208–10,214, doi:10.1002/2016GL070974.

Stress rotation as a measure of the background stress

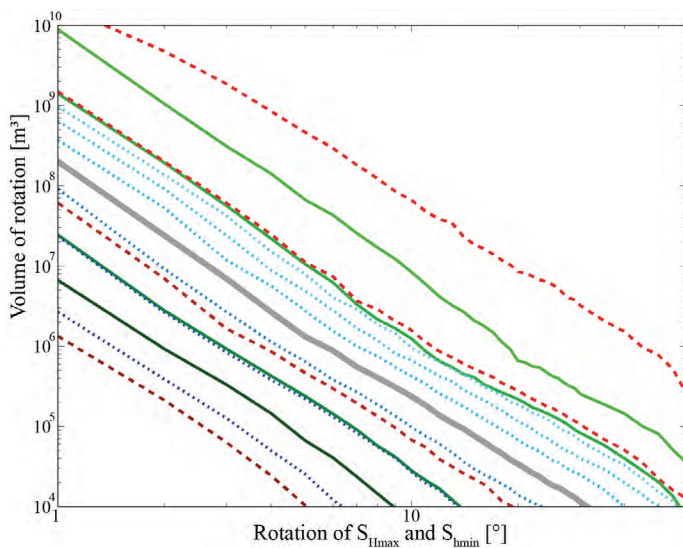
by Moritz Ziegler (GFZ Potsdam)

Fluid injection operations into geo-reservoirs are known to perturb the in-situ stress state by changes in the pore pressure. These stress changes can increase the risk of induced seismic events. However, the fluid injection does not only alter the pore pressure but a change in orientation of the principal stress axes related to massive fluid injections has been observed (Martinez-Garzon et al., 2013).

We use a thermo-hydro-mechanical numerical modelling approach to investigate the key driving factors and mechanisms that control the rotation

of the principal stress axes. We use the commercial finite element code Abaqus to simulate the injection of fluids into a generic reservoir setting. We then alter individual parameters of the reservoir and the injected fluid in order to investigate the sensitivities of the stress rotation.

We find that reservoir permeability, fluid injection rate, and the initial stress state (especially the differential stress) are the key factors that control the angle of stress rotation. Other reservoir properties such as porosity or injection parameters such as the temperature of fluid only play a negligible role. In particular, we find that thermal effects do not significantly contribute to stress rotations. For common reservoir types and a reasonable differential stress and reservoir treatment the occurrence of significant stress rotations is limited to those with a permeability of less than approximately 10-12 m². Higher permeability effectively prevents stress rotations to occur. Thus, according to these general findings the observed principal stress axes rotation can be used as a proxy of the initial differential stress provided that rock permeability and fluid injection rate are known a priori.



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Stress rotation

The changes in stress rotation angle (x-axis) for different volumes (y-axis) each in comparison to a reference scenario (grey). An increase in injection rate (blue, 25l/s – 175 l/s), a decrease in differential stress (green, 8.3 MPa – 0.6 MPa), and a decrease in permeability (red, 5x10 – 1.5x10⁻¹⁵) lead to an increasing stress rotation angle.

Key Reference

Martínez-Garzón, P.; Bohnhoff, M.; Kwiatak, G. & Dresen, G. Stress tensor changes related to fluid injection at The Geysers geothermal field, California Geophysical Research Letters, 2013, 40, 2596-2601, doi: 10.1002/grl.50438

Ziegler, M. O.; Heidbach, O.; Zang, A.; Martínez-Garzón, P. & Bohnhoff, M. Estimation of the differential stress from the stress rotation angle in low permeable rock Geophysical Research Letters, Wiley-Blackwell, 2017, 6761-6770, doi: 10.1002/2017GL073598

Visualization tool for the 3D stress tensor data from THM models

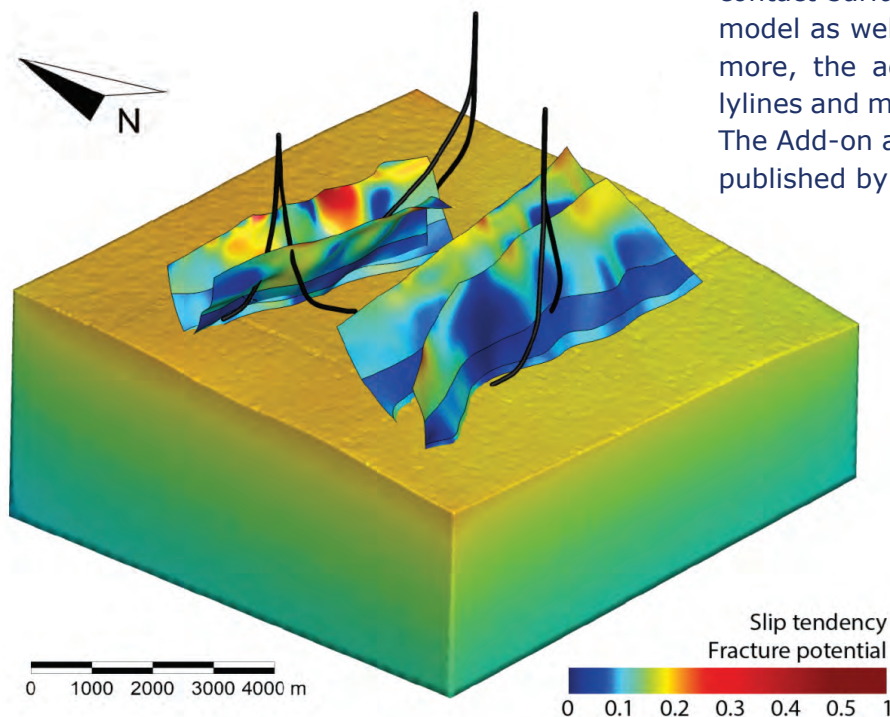
by Oliver Heidbach (GFZ Potsdam)

For the visualization and analysis of the stress field from 4D thermo-hydro-mechanical (THM) numerical model results two main technical steps are necessary. First, one has to derive from the six independent components of the stress tensor scalar and vector values such as the orientation and magnitude of the maximum and minimum horizontal stress, stress ratios, differential stress. It is also of great interest to display e.g. the normal and shear stress with respect to an arbitrarily given surface. Second, an appropriate geometry should be given such as cross sections, profile e.g. for borehole pathways or surfaces on which the model results and further derived values are

interpolated. This includes the three field variables temperature, pore pressure and the displacement vector.

To facilitate and automate these steps the add-on GeoStress for the professional visualization software Tecplot 360 EX (version R2 2017) has been programmed. Besides the aforementioned values derived from the stress tensor the tool also allows to calculate the values of Coulomb Failure Stress (CFS), Slip and Dilation tendency (ST and DT) and Fracture Potential (FP). GeoStress also estimates kinematic variables such as horizontal slip, dip slip, rake vector of faults that are implemented as contact surfaces in the geomechanical-numerical model as well as the true vertical depth. Furthermore, the add-on can export surfaces and polylines and map on these all available stress values. The Add-on as well as example and input files are published by Stromeyer and Heidbach (2017a,b).

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3D stress visualization

Model results of the branch model; shown is top basement and faults in the overlying hydrothermally exploited Malm units at approximately 4 km depth; black lines are projected drilling trajectories. On the faults slip tendency is displayed which is a measure of the reactivation potential of the fault with values between zero and one (=reactivation). In the volume the same color code is usage for fracture potential which is a measure to create new fractures between zero and one (=fracture initiation).

Key References

- Stromeyer, D., Heidbach, O. (2017): Manual of the Tecplot 360 Add-on GeoStress, WSM Technical Report 17-01, GFZ German Research Centre for Geosciences, 49 p., <http://doi.org/10.2312/wsm.2017.001>
- Stromeyer, Dietrich; Heidbach, Oliver (2017): Tecplot 360 Add-on GeoStress. GFZ Data Services. <http://doi.org/10.5880/wsm.2017.001>

AAPG Asia Pacific Region workshop on the “Pore Pressure and Geomechanics from Exploration to Abandonment”

The past 30 years have seen a rapidly growing recognition of the important role geomechanics and pore pressure analysis plays in the hydrocarbon industry. Geomechanics and pore pressure analysis originally gained prominence in the late 1980s in planning and drilling wells, with issues such as wellbore stability and high pressures recognized as leading causes of lost-time incidents in expensive deep-water drilling operations. Since these beginnings, geomechanics and pore pressure have been used in an increasingly broad capacity, and are now important elements throughout the entire field life-cycle. Geomechanics and pore pressure provide valuable insights and applications in acreage selection and prospect risking, well planning and field development planning, completions, reservoir modeling, enhanced recovery, and eventual field abandonment. Furthermore, geomechanics in particular has been an essential aspect of unconventional hydrocarbon production, providing critical inputs for fracture stimulation, directional drilling and field planning that have drastically changed the industry.

This 2 day workshop will bring together a wide range of geoscientists, engineers and managers to highlight the important and varied roles that geomechanics and pore pressure play from initial exploration phases through to field abandonment. This workshop will also highlight the key aspects and elements that are unusual or unique to geomechanics and pore pressure analysis in Australia and Asia, where basins are often characterized by complicated geology, variable and high-magnitude stress states and anomalous overpressures. Key themes of the workshop will follow the use of geomechanics and pore pressure throughout the well life-cycle, including their use in:

- developing play concepts and prospect risking;
- well planning and optimal well design;
- safe and efficient real-time operations;
- field appraisal and development;
- completions and fracture stimulation;
- reservoir geomechanics and enhancing field production, and;
- successful well and field abandonment.

Call for Abstracts Ends on 30 January, 2018 - More information at: <https://goo.gl/Fzzpxc>

Publications related to research on crustal stress

- Alt II, R. C. and M.D. Zoback (2017). In Situ Stress and Active Faulting In Oklahoma. *Bull. Geol. Soc. Am.*, 107, 216-228, <http://doi.org/10.1785/0120160156>
- Heidbach, O., Rajabi, M., Reiter, K., Ziegler, M. 2016. World Stress Map 2016, GFZ Data Services, doi:10.5880/WSM.2016.002.
- 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: 182-192.
- Lund Snee, J.-E., Zoback, M.D. (2018). State of stress in the Permian Basin, Texas and New Mexico: Implications for Induced Seismicity. *The Leading Edge*.
- Lund Snee, J.-E., & Zoback, M. D. (2016), State of stress in Texas: Implications for induced seismicity, *Geophys. Res. Lett.*, 43, 10208-10214, <http://doi.org/10.1002/2016GL070974>
- Rajabi, M., Heidbach, O., Tingay, M. and K. Reiter (2017). Prediction of the present-day stress field in the Australian continental crust using 3D geomechanical-numerical models. *Australian J. Earth Sc.*, 64(4), 435-454, <http://doi.org/10.1080/08120099.2017.1294109>
- Rajabi, M., Tingay, M. and O. Heidbach (2016). The present-day stress field of New South Wales, Australia. *Australian Journal of Earth Sciences*, 63(1), 1-21, <http://doi.org/10.1080/08120099.2016.1135821>
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- Ziegler, M., Heidbach, O., Reinecker, J., Przybycin, A. M. and M. Scheck-Wenderoth (2016). A multi-stage 3-D stress field modelling approach exemplified in the Bavarian Molasse Basin. *Solid Earth*, 7, 1365-1382, <http://doi.org/10.5194/se-7-1365-2016>
- Zoback, M.L. (1992). Stress field constraints on intraplate seismicity in eastern North America. *Journal of Geophysical Research*, 97(B8): 11,761-11,782, doi: 10.1029/92JB00221.