Understanding injection-induced seismicity: Temporal link between pore pressure increase and shear-wave anisotropy

Keith A. Nolte[1], Georgios P. Tsoflias[1], Tandis S. Bidgoli[2] and W. Lynn Watney[2]
[1]Department of Geology, The University of Kansas, Lawrence, KS
[2]Kansas Geological Survey, The University of Kansas, Lawrence, KS

Local shear-wave anisotropy in Wellington oil field, KS

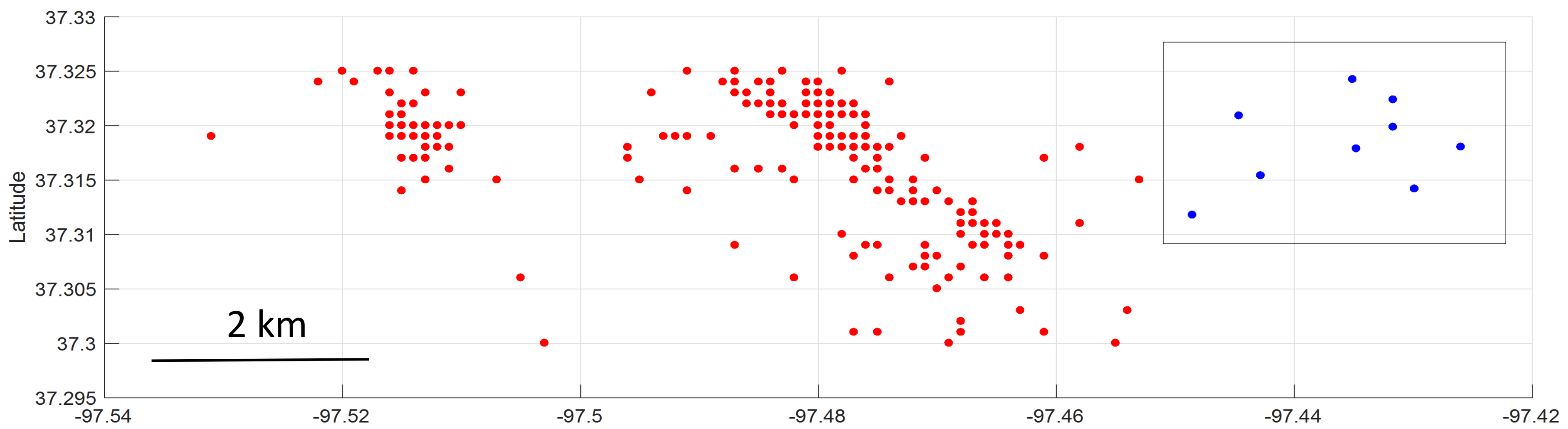


Figure 7. Map of earthquakes used for the analysis results shown in Figure 8. Earthquakes were chosen to the west of the monitoring array over a two-month period to limit azimuthal and temporal variability.

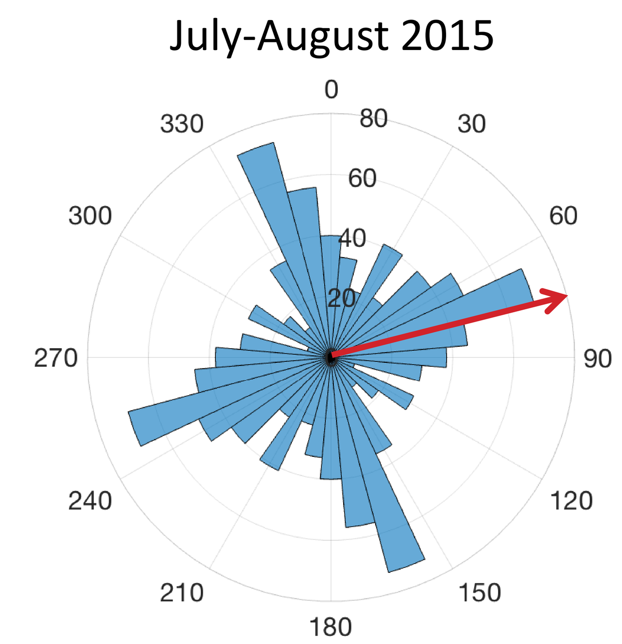
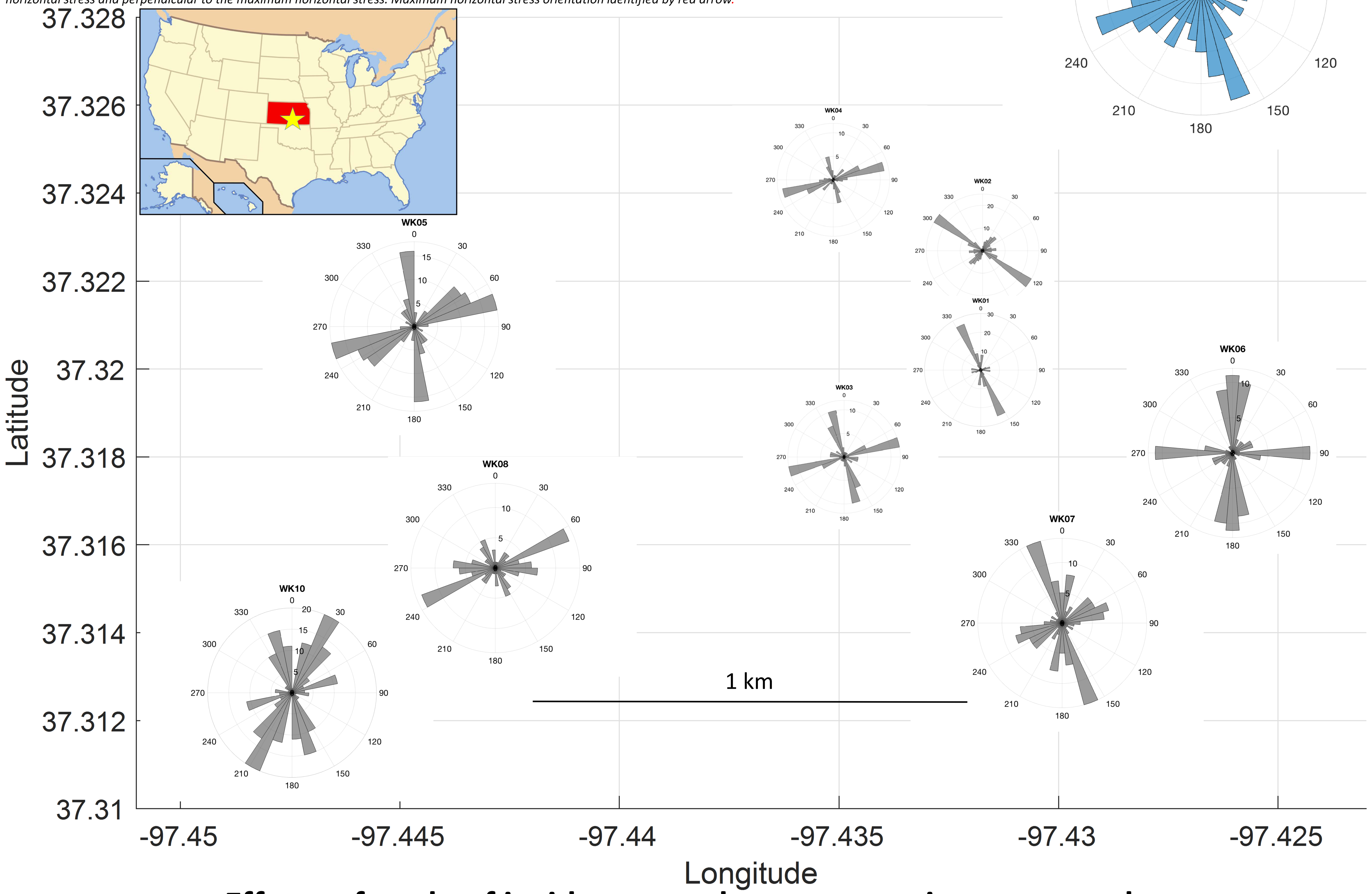


Figure 8. Map of stations with plots of the phi orientations for each station. Phi orientations perpendicular to maximum horizontal stress can be seen at nearly all stations. φ and dt were calculated for earthquake-station pairs that had a clear shear-wave arrival with signal-noise ratio greater than 2 and rms energy on the horizontal channels twice as much as rms energy on the vertical channel. (right) polar histogram of all anisotropy orientations, showing that a comparable number of orientations are both in line with the maximum horizontal stress and perpendicular to the maximum horizontal stress. Maximum horizontal stress orientation identified by red arrow.



Effects of angle of incidence on shear-wave anisotropy results

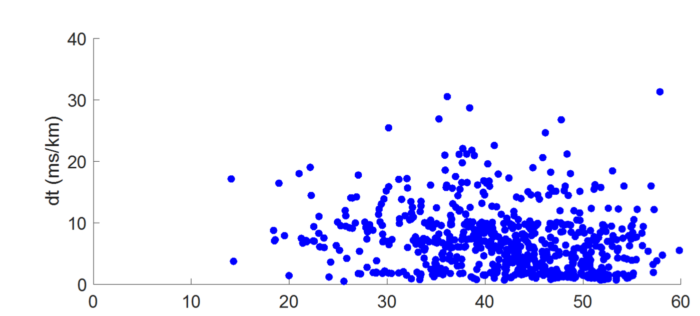


Figure 9. Plot of geometric angle of incidence out to 60 degrees from vertical versus dt solutions corrected for hypocentral distance. No major change occurs in dt out to 60 degrees.

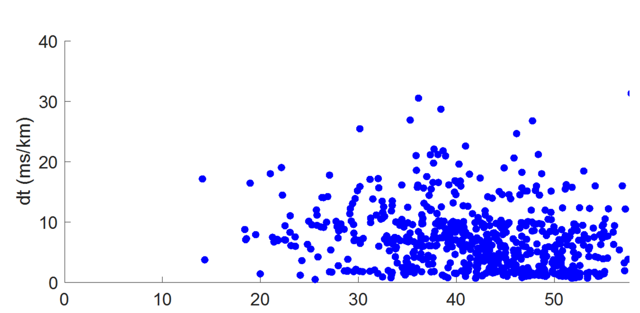


Figure 10. Plot of a 2D histogram of the data from figure 9, showing more clearly the volume of data per solution. No change in dt indicates higher angle of incidences can be used.

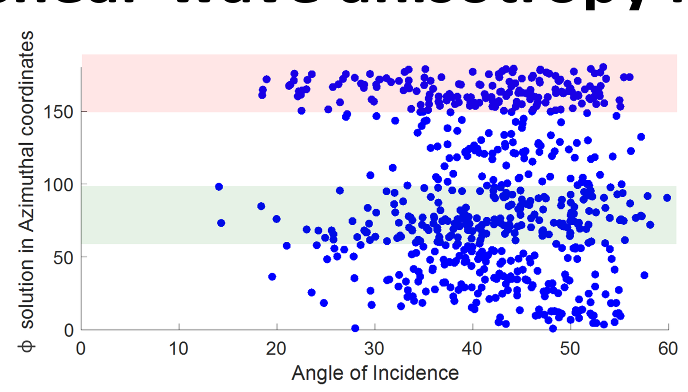


Figure 11. Plot of geometric angle of incidence out to 60 degrees from vertical versus φ solutions in azimuthal orientation. Two major clusters of φ solutions can be seen One approximately parallel to the maximum horizontal stress (green) and one approximately perpendicular to the maximum horizontal stress (red).

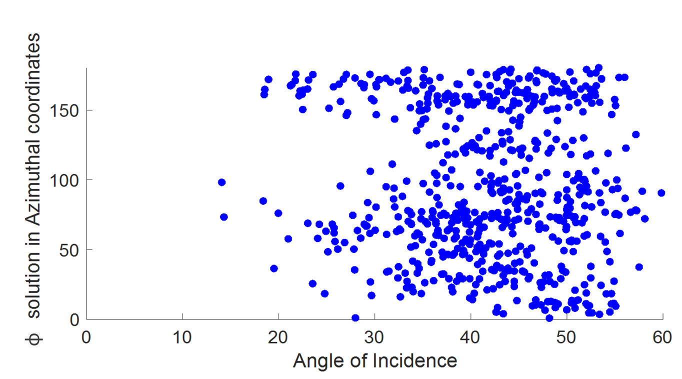
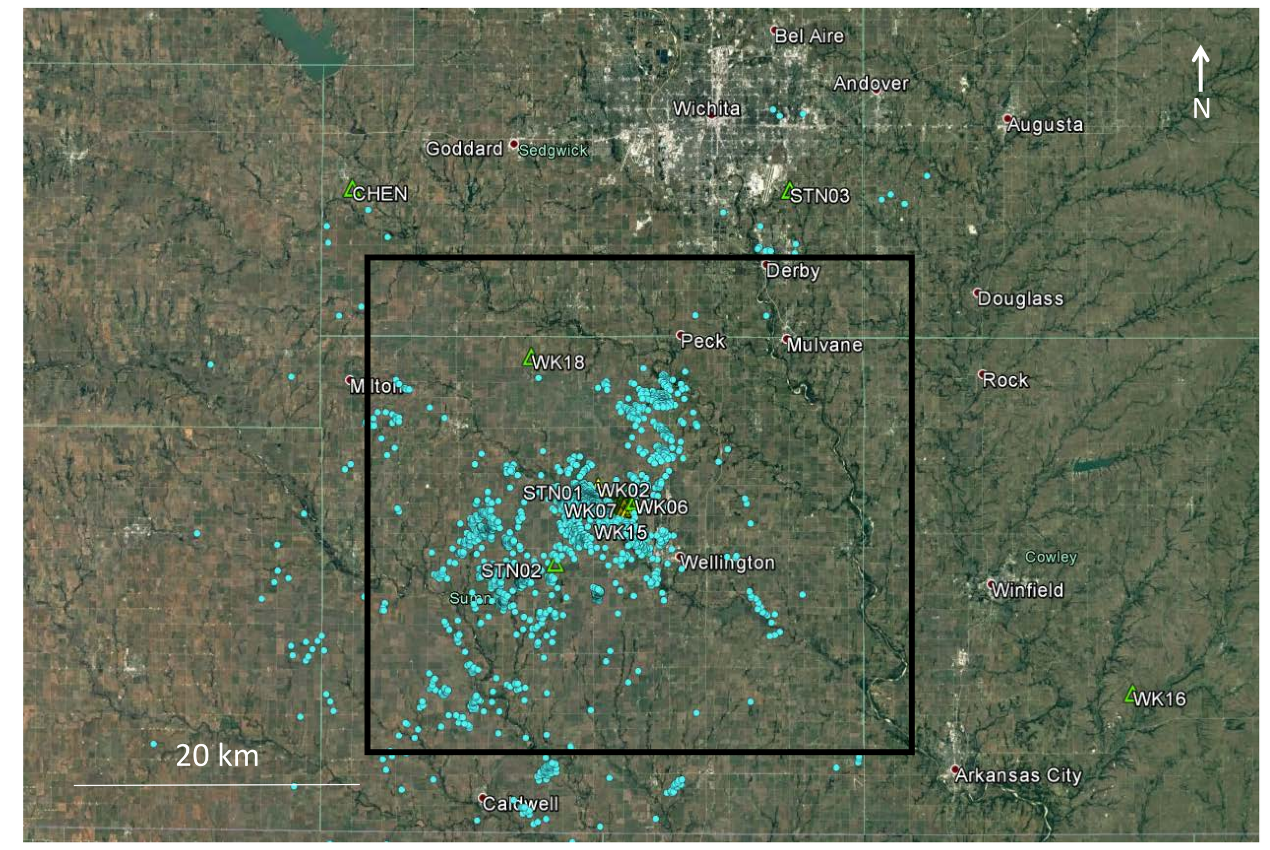


Figure 12. Plot of a 2D histogram of the data from figure 11, clearly showing the two trends in the yellow color, depicting more solutions in that value. No change in φ outside of the classical shear-wave window of 45-50 degrees indicates that higher angles of incidence can be used.

Wellington Earthquake Catalog 2015 - 2017



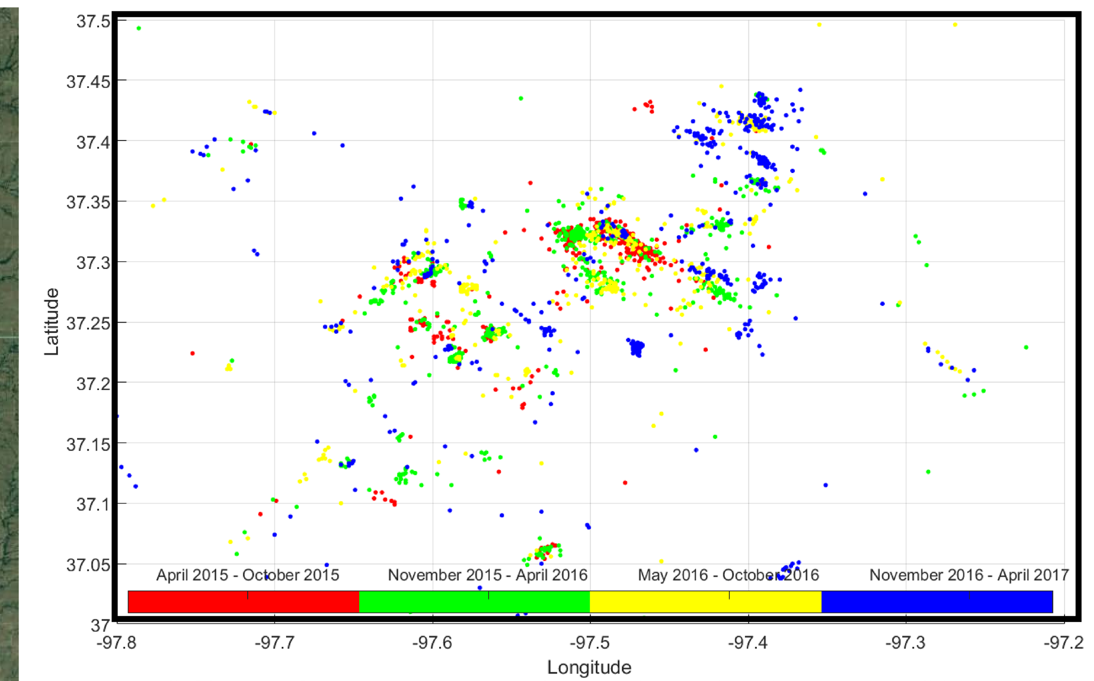
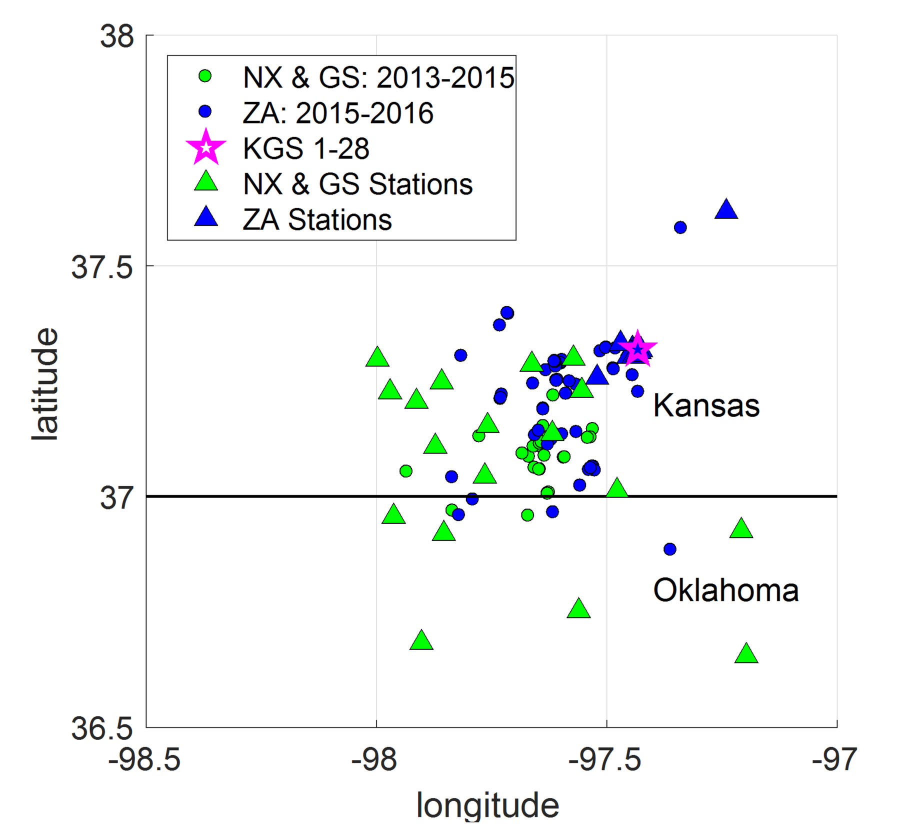
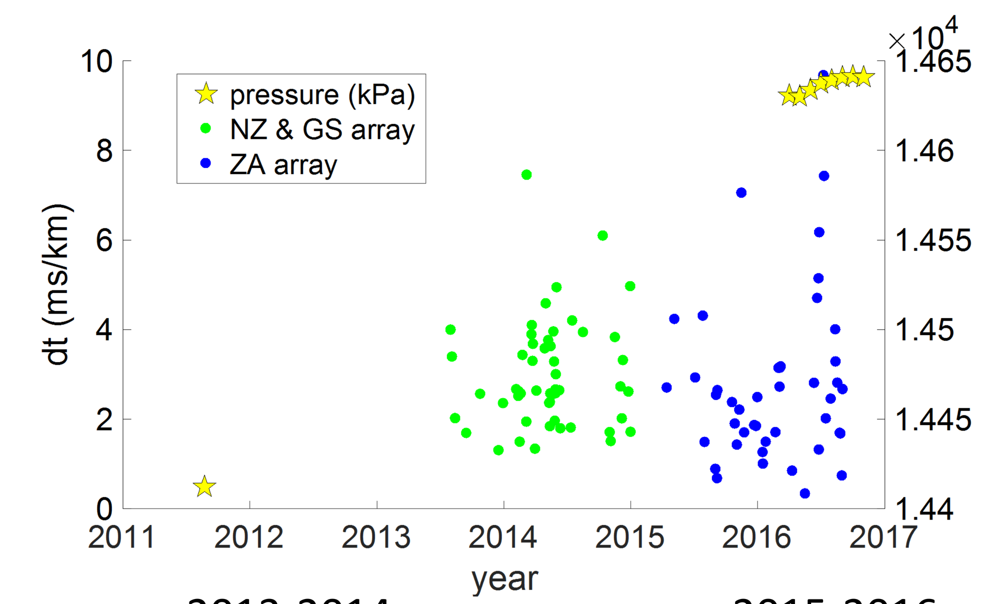


Figure 13.(left) Map of Sumner County, KS, showing the earthquake epicenters (blue dots) and station locations (green triangles).

Figure 14. (top) Map of Sumner County, KS, showing the earthquake catalog color coded temporally, where red are the oldest earthquakes and blue the most recent. Earthquakes can be seen migrating towards the northeast.

Shear-wave anisotropy in Sumner County, KS





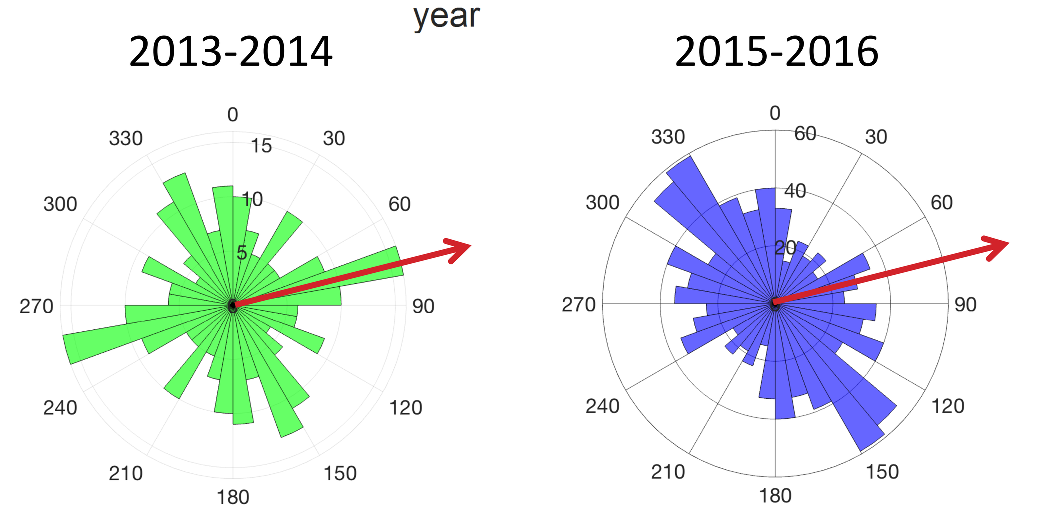


Figure 15. (top) Map of station and earthquake locations used for analysis of Sumner County shear-wave anisotropy. Earthquakes were chosen based on clear shear-wave arrival and of magnitude 2 or greater

Figure 16. (top right) Plot of dt vs. time for Sumner county earthquakes, along with downhole pressure monitoring in KGS well 1-28. (right) Plot of phi solutions separated by time show change from a mix of phi solutions that are inline and perpendicular to the maximum horizontal stress (green) to a mostly flipped phi solution in the later earthquakes (blue).

Results

- **Temporal-spatial trends in the Wellington Earthquake Catalog (figure 14) indicate that seismicity is moving to the northeast over time. This trend is consistent with advancing pore pressure increase from high volume wastewater injections to the south and west.**
- **Shear-wave anisotropy analysis shows ϕ values orientated parallel to maximum horizontal stress and perpendicular to it suggesting the subsurface is critically stressed by pore fluid pressure (figure 8). This observation is direct seismological evidence relating pore fluid pressure to earthquakes in KS and OK.**
- **Temporal anisotropy analysis reveals a change in ϕ, from in line and perpendicular to maximum horizontal stress in 2013-2014, to primarily perpendicular in 2015-2016 (figure 16).**
- **Shear-wave splitting methods could be used to mitigate seismic hazard associated with injection induced seismicity through mapping flips in ϕ and changes in dt.**

Acknowledgements

This research has been supported by grants from the Kansas Geological Survey and the Kansas Interdisciplinary Carbonates Consortium (KICC) as well as DOE contract (DE-FE0006821). Equipment has also been on loan through IRIS and PASSCAL.

References

1) Ellsworth, W.L., 2013, Injection induced earthquakes, Science, v. 341, 1225942.
2) Garnero, E., 2017, School of Earth and Space science, Arizona State university, personal website: http://garnero.asu.edu/
3) Silver, P.G., and Chan, W.W., 1991, Shear wave splitting and subcontinental mantle deformation, *Journal of Geophysical Research, v. 96, p.* 16429-16454
4) Zinke, J.C. and Zoback, M.D., 2000, Structure-related and stress-induced shear-wave velocity anisotropy: observations from microearthquakes near the Calaveras fault in central California, *Bulletin of the Seismological Society of America*, v. 90, p. 1305-1312.
5) Crampin, S., Volti, T., Chastin, S., and A. Gudmundsson*, Indication of high pore-fluid pressures in a seismically-active fault zone,* Geophys J Int. 2002;151(2):F1-F5.

KICC
Kansas Interdisciplinary Carbonates Consortium

SEG
SOCIETY OF EXPLORATION GEOPHYSICISTS

Abstract: Seismicity in the US midcontinent has increased by orders of magnitude over the past decade. Spatiotemporal correlations of seismicity to wastewater injection operations have suggested that injection-related pore fluid pressure increases are inducing the earthquakes. We present direct evidence linking earthquake occurrence to pore pressure increase in the US midcontinent through time-lapse shear-wave anisotropy analysis. Since earthquake frequency increased in 2013 we observe that **the orientation of the fast shear-wave has flipped from inline with the maximum horizontal stress to inline with the minimum horizontal stress, a change associated with critical pore pressure build up**. The time delay between fast and slow shear wave arrivals has increased through time, indicating a corresponding increase in anisotropy induced by pore pressure rise. *In-situ* near-basement fluid pressure measurements corroborate the continuous pore pressure increase revealed by the shear-wave anisotropy analysis over the earthquake monitoring period.

Background

Shear-Wave Splitting

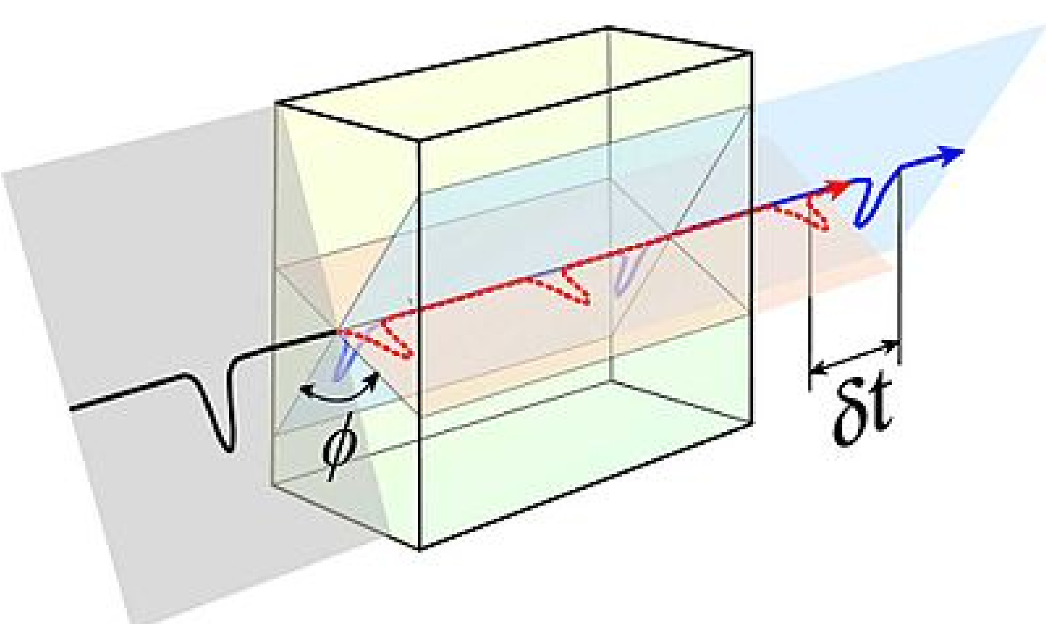
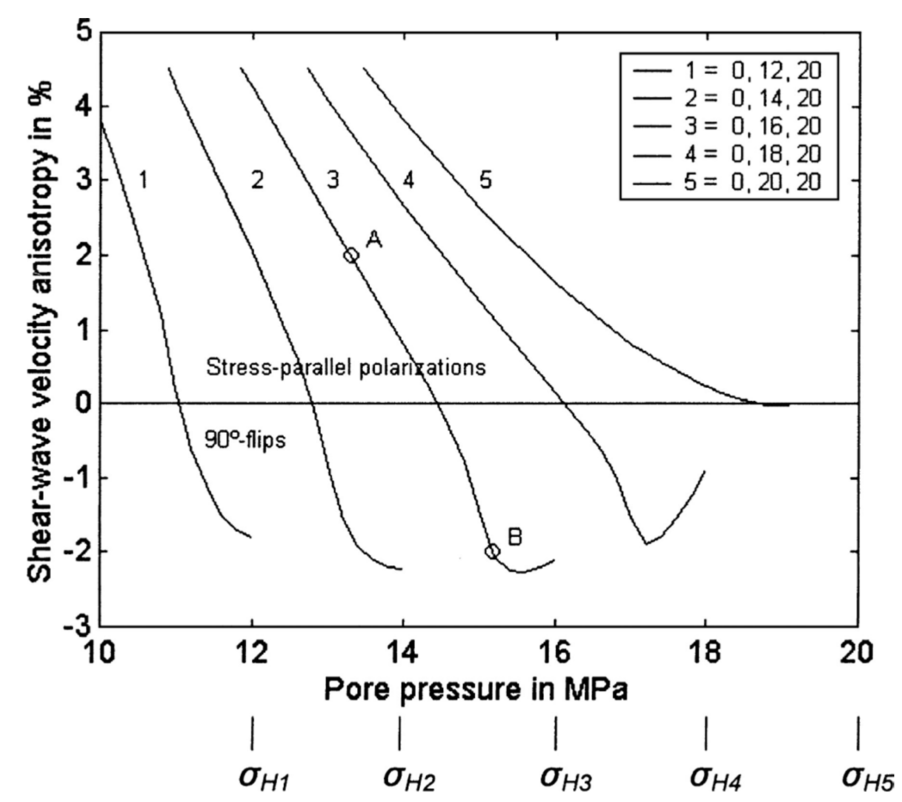


Figure 1. *Example of how a shear-wave separates into a fast and slow component in an anisotropic medium. From Garnero, 2017.*

- Shear wave splits to “fast” and “slow” waves when it travels through an anisotropic medium
- Fast shear-wave travels parallel to the anisotropy
- dt is the separation in time between the fast and slow shear-wave arrivals
- ϕ is the orientation of the fast shear-wave (fig. 4)
- Increasing pore pressure increases seismic anisotropy by dilatation of fractures and results in increased dt
- Increasing pore pressure results in flipping the orientation of ϕ by 90 degrees (figs. 5)

Flips in Shear-Wave Anisotropy



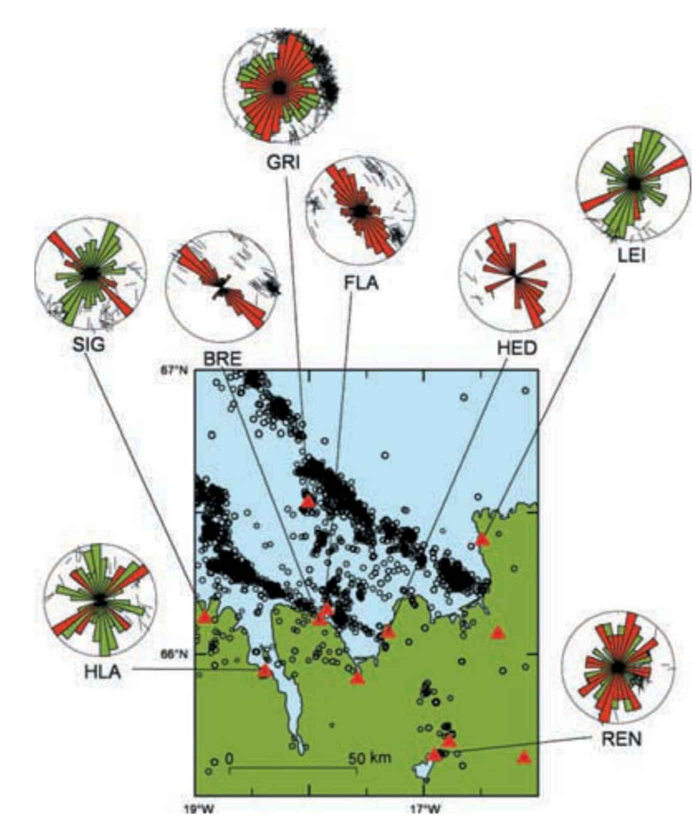


Figure 2 *(left) Modified from Crampin et al(2002) shows that as pore fluid pressure increases to similar magnitude as the maximum horizontal stress, the phi orientation can become flipped, as seen in figure 3.*

Figure 3 *(right) Modified from Crampin et al(2002) shows phi orientations that are both flipped and in line with maximum horizontal stress, indicative of high pore fluid pressure.*

Workflow

1. **Earthquakes near the shear-wave window with good SN and clear shear-wave arrivals were identified (fig. 4)**
2. **Shear-wave arrival is analyzed in hodograms for first arrival identification (fig. 5)**
3. **Hodograms containing the first arrival are processed (fig. 6)**
4. **Processed first arrivals produce a ϕ and dt (fig. 8, 9 & 11)**

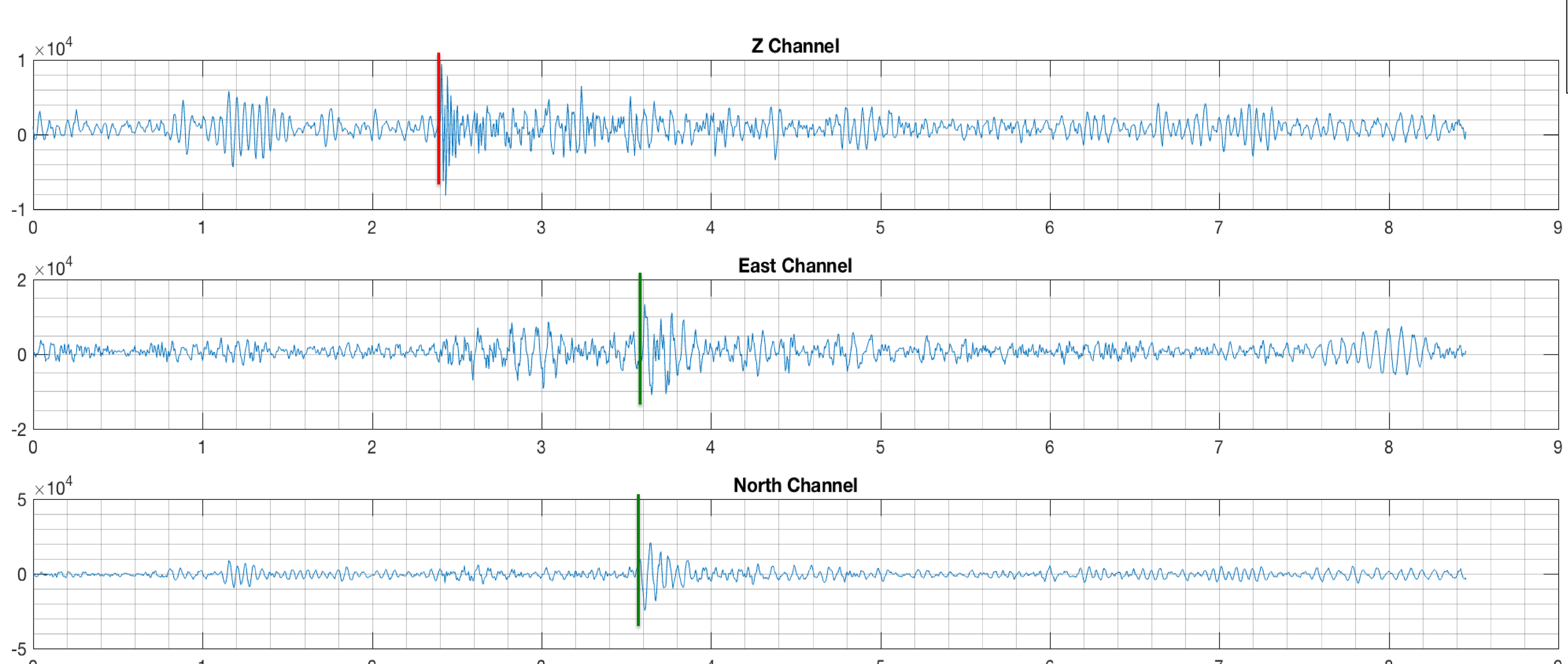
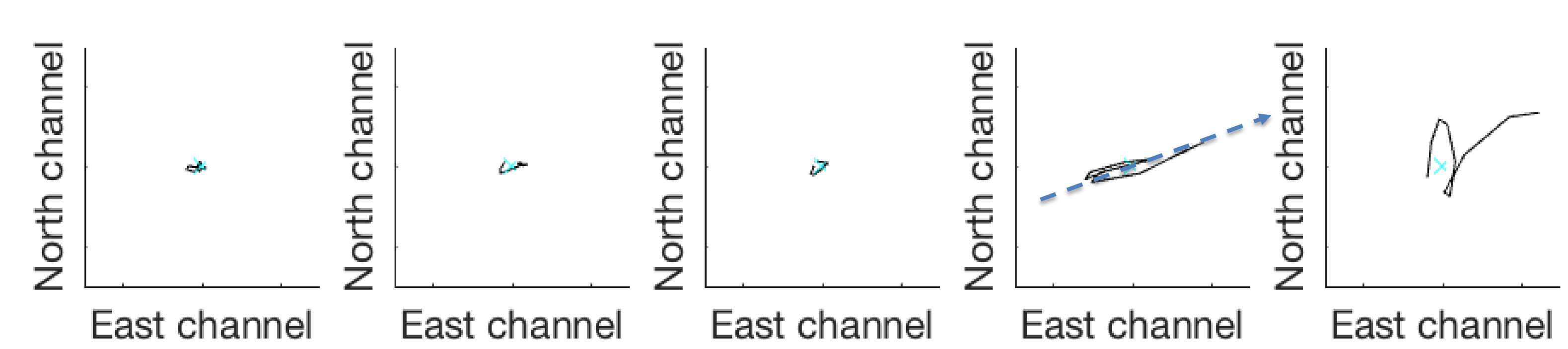


Figure 4. *Example of local earthquake with p-wave arrival picked on Z channel in red and s-wave picked on horizontal channels in green. This event meets the criteria of a clear shear-wave, signal to noise ratio above 2 and higher energy on horizontal components than vertical component*

First arrival 90⁰ aligned with regional stress



First arrival flipped from regional stress

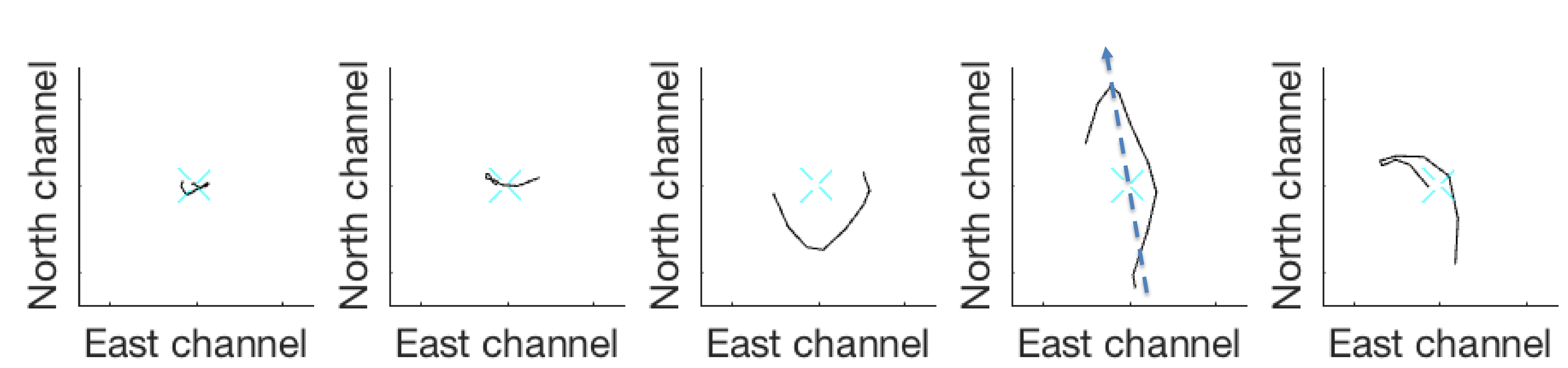


Figure 5. *Hodogram plots of shear-wave first arrival. Each plot is 10 samples or 0.05 seconds. The first row has a shear-wave polarization of approximately west-east which is in line with the maximum horizontal stress. The second row has a shear-wave polarization that is approximately north-south which is perpendicular to the maximum horizontal stress*

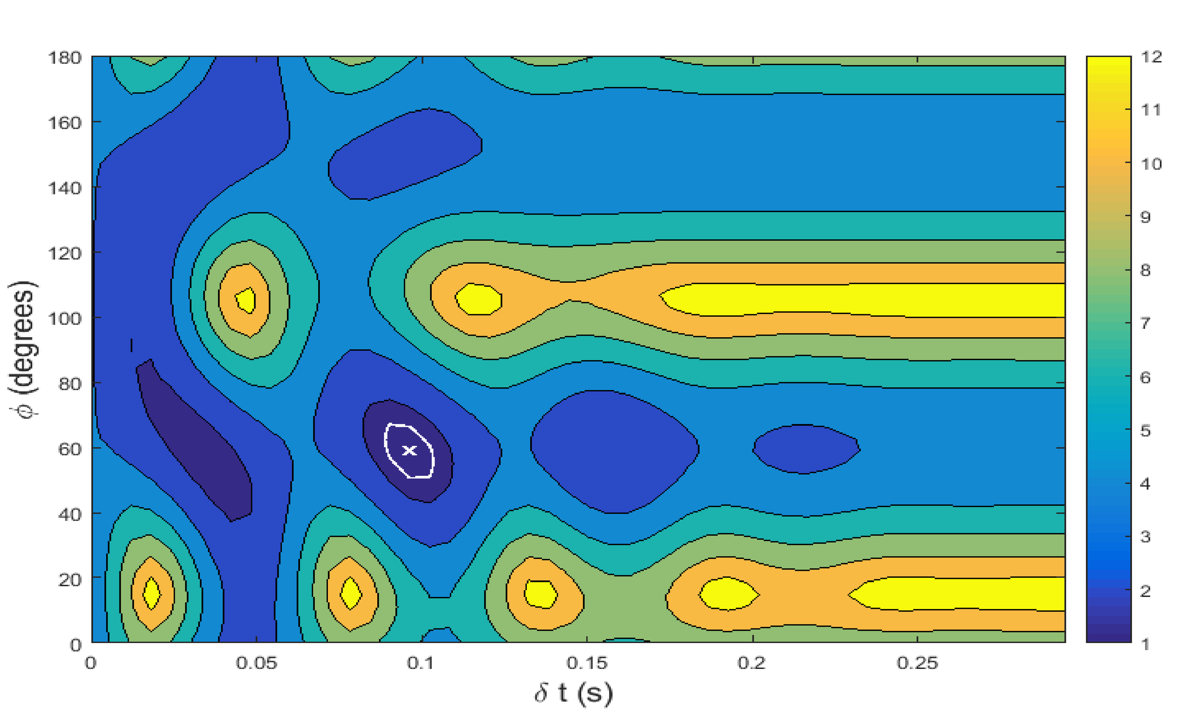


Figure 6. *Plot of the minimization of the second eigenvalue (λ_2) from Figure 3. in ϕ and δt space. Minimizing λ_2 is the chosen mathematical way to return a covariance matrix that is closest to being singular. With no noise the covariance matrix will return λ_1 as the only non-zero eigenvalue (Silver and Chan, 1991). The white marker (x) is the best solution and the white line is an estimate of the 95% confidence interval. Angles are from 0° to 180°, where 0° is west and 180° is east. This solution of approximately 60° is therefore 30° west of north or 330°.*