Does Stress Drop Vary with Depth?

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Summary and Motivation

We combine earthquake spectra from multiple studies to investigate whether the increase in stress drop with depth, that is often observed in the crust, is real or an artefact of variation in attenuation (Q) with depth.

Shearer et al. [2006] developed spectral decomposition, in which spectra from large numbers of earthquakes and stations are stacked and inverted to separate the source radiation (event spectra) from the effects of path and site. This approach stabilizes the results and decreases the uncertainties by stacking a large number of recordings. The empirical path and attenuation corrections are usually assumed to be the same for all earthquakes in the study region, regardless of source depth.

We test this assumption by investigating whether a realistic increase in Q with depth (as is widely observed) could remove some of the observed apparent increase in stress drop with depth.

Data

We combine event spectra, obtained from spectral decomposition [*Shearer et al.*, 2006], from over 50,000 earthquakes (M0-5) from 13 studies in:

Northern California

Hayward Fault [*Hardebeck & Aron*, 2009]
Bay Area: Livermore Region & Combined San Andreas & Hayward Faults [*Trugman & Shearer*, 2018]
Parkfield SAF [*Zhang et al.*, 2019]

Southern California

Salton Sea: Geothermal Field and Southern SAF [*Chen & Shearer*, 2011]
Landers, Big Bear, & Hector Mine aftershocks, San Jacinto Trifurcation zone, & Yuha Desert [*Trugman & Shearer,* 2017]
Landers (6 km cube) [*Shearer et al.*, 2019],
San Gorgonio Pass [*Goebel et al.*, 2015],
Ridgecrest Aftershocks [*Trugman,* 2020];

Nevada

Mogul Sequence [Ruhl et al., 2020]

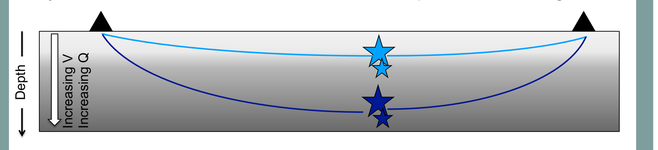
Central USA

Kansas [*Trugman et al.*, 2017],
Guthrie sequence, Oklahoma [*Chen & Abercrombie*, 2020
Prague sequence, Oklahoma; [*Pennington,et al.,* 2020].

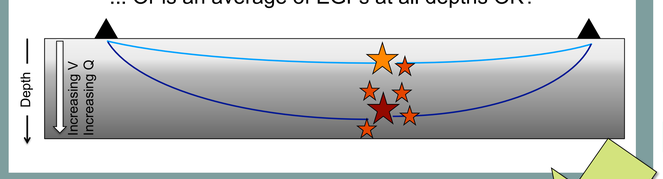
Empirical Path Correction:

In individual event EGF analysis, EGF event must be collocated with target event (e.g. *Abercrombie,* 2015).
In Spectral Decomposition inversions (e.g. *Shearer et al.,* 2006) homogeneous attenuation structure is assumed.
What if attenuation varies with depth, as is often observed?

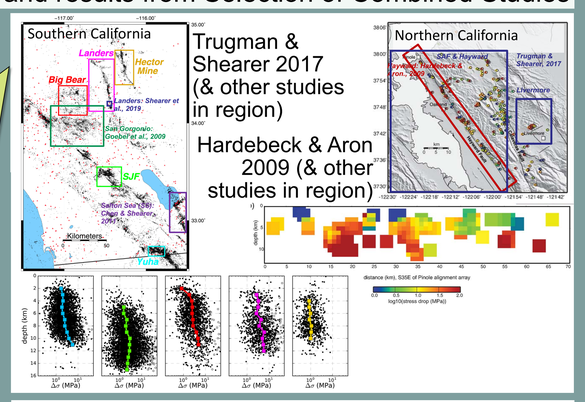
Do you need Small EGF events at same depth as each large one?



... Or is an average of EGFs at all depths OK?

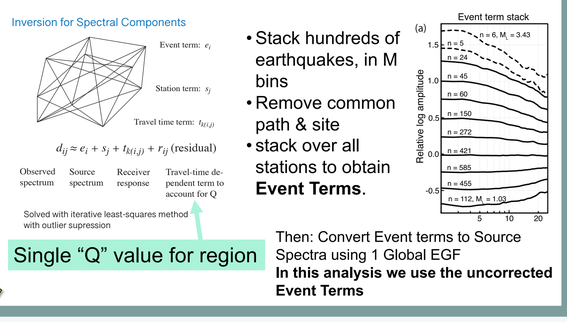


Location and results from Selection of Combined Studies



Spectral Decomposition and Global EGF

Analyse a large data set together — Shearer *et al.*, 2006



- Stack hundreds of earthquakes, in M bins
- Remove common path & site
- stack over all stations to obtain **Event Terms**.

Single "Q" value for region

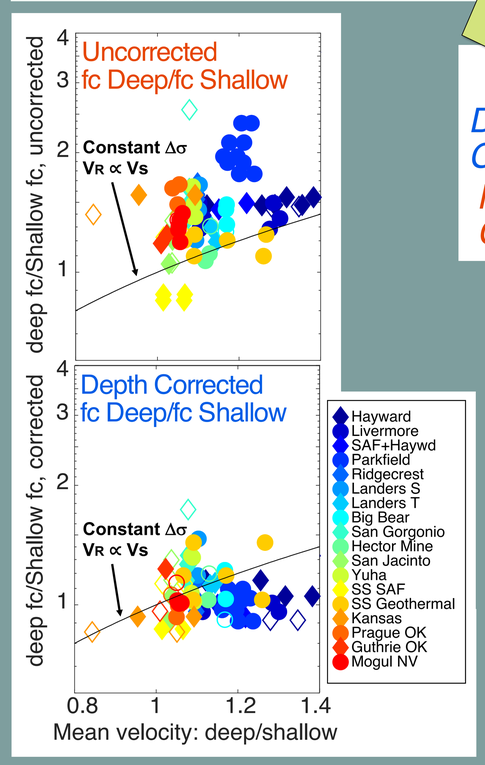
Then: Convert Event terms to Source Spectra using 1 Global EGF
In this analysis we use the uncorrected Event Terms

Conclusions

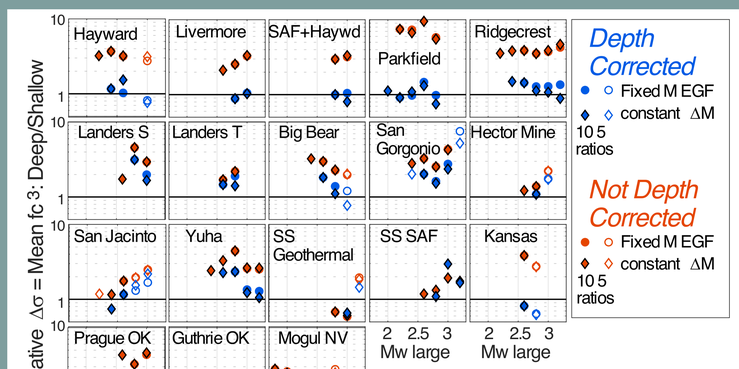
- **Without** any correction for depth-dependent attenuation: systematic increase in stress drop with depth (or increase in rupture velocity), as has previously been observed.
- **With** an empirical attenuation correction: depth dependence of stress drop systematically decreases, often becoming negligible.
- The largest corrections are in regions with the largest velocity increase with depth.
- Spectral decomposition analyses, and similar style inversions, should not assume path terms are independent of source depth, and should more explicitly consider depth-dependent attenuation models in future.

Spectral Shape & Velocity Structure

The increase in high frequency energy with depth is higher when the velocity gradient is steeper. A simple depth-dependent empirical path correction removes much of previously reported increase in stress drop with depth



Spectral Fitting Results from All Data Sets

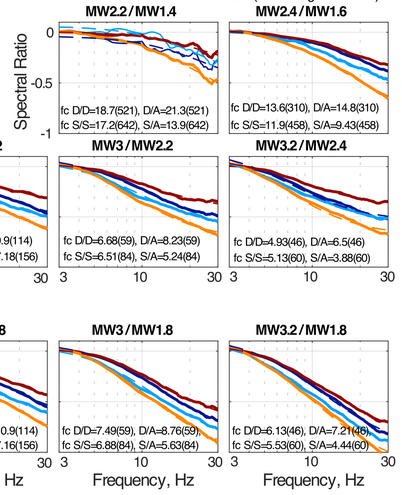


The approximate, empirical correction for depth variation in path effects systematically decreases difference in stress drop between deep and shallow events, for all M combinations

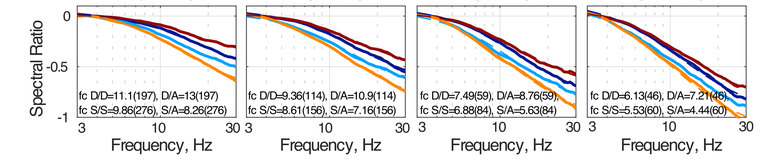
Constant ΔM Between Events

Ridgecrest Aftershocks (after Trugman 2020)

Depth Corrected — Deep/deep (>7km), Shallow/Shallow (<3km)
Not Depth Corrected — Deep/All, Shallow/All



Constant M EGF

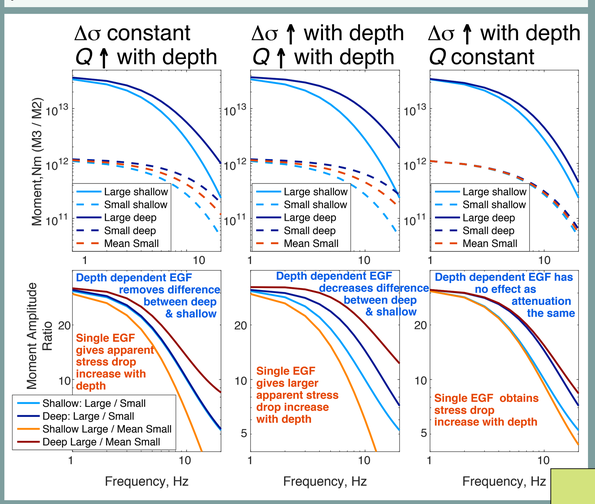


Spectral Fitting: Example Ridgecrest Aftershocks

We use simple Brune model to fit spectral ratios between average large and small events in a range of M bins, as a function of source depth. We find using EGF events from the same depth range as the large events significantly decreases the difference between the deep and shallow event corner frequencies, regardless of M.

Consider some simple cases – what do we predict?

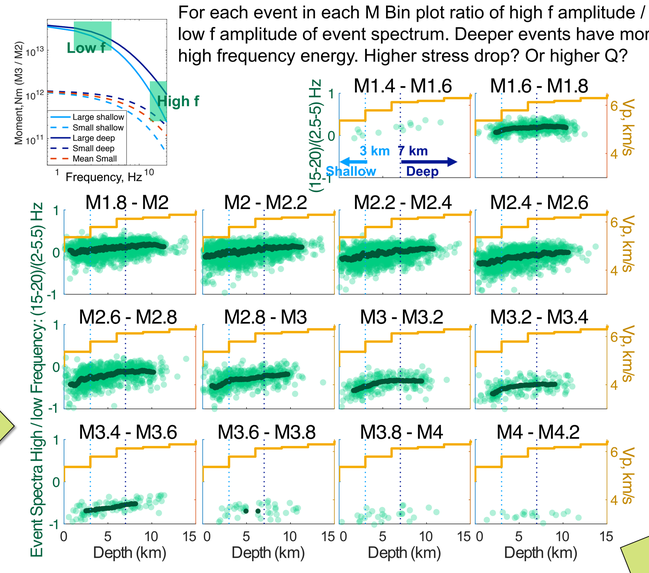
A simple synthetic test suggests calculating ratios between earthquakes in different M bins at different depths can distinguish depth-dependent source from depth-dependent path effects



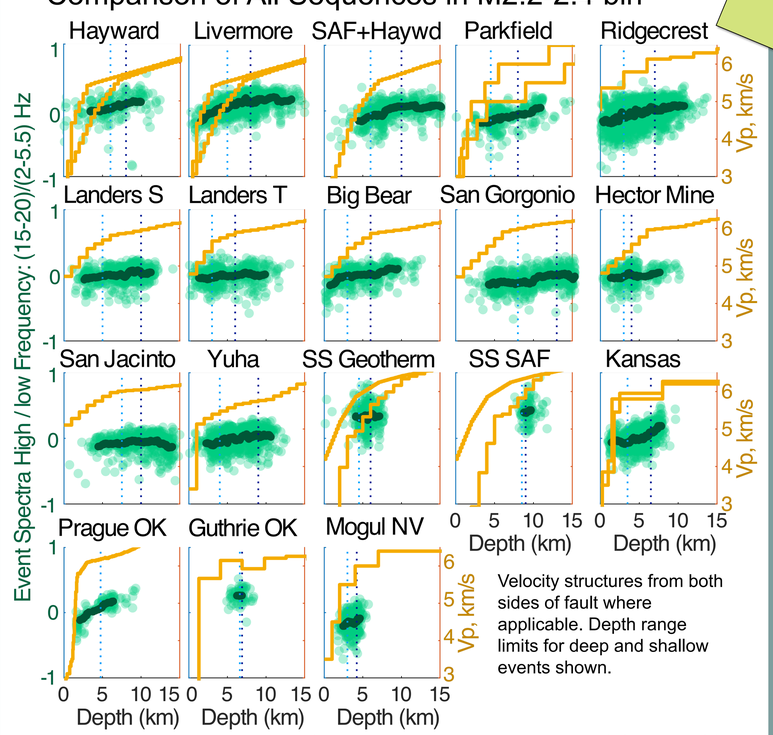
Methods – Apply Same Tests to Data

For different magnitude bins, we compare the ratio of the high- to low-frequency amplitudes and find that the relative high-frequency content (and corner frequency) always increases with increasing earthquake depth. By analyzing spectral ratios between large and small events as a function of source depth, we explore the relative importance of source and attenuation contributions to the observed depth dependence in high-frequency radiation and corner frequency.

Example: Ridgecrest Aftershocks (after Trugman 2020)



Comparison of All Sequences in M2.2-2.4 bin



Velocity structures from both sides of fault where applicable. Depth range limits for deep and shallow events shown.

Deeper events have more high frequency energy. Higher stress drop? Or higher Q?
Larger effect when steeper velocity gradient?

References

Studies Included:

Chen, X., and Shearer, P. M. (2011), Comprehensive analysis of earthquake source spectra and swarms in the Salton Trough, California, *J. Geophys. Res.*, 116, B09309, doi:10.1029/2011JB008263.

Chen, X., R E Abercrombie, Improved approach for stress drop estimation and its application to an induced earthquake sequence in Oklahoma, *Geophys. J Int,* 10.1093/gji/ggaa316, **223**, 1, (233-253), (2020).

Goebel,T. H. W., E. Hauksson, P.M. Shearer, J.P. Ampuero, Stress-drop heterogeneity within tectonically complex regions: a case study of San Gorgonio Pass, southern California, *Geophys. J Int.*, 202, Issue 1, 1 July 2015, Pages 514–528, https://doi.org/10.1093/gji/ggv160

Hardebeck, J. L., A. Aron, Earthquake Stress Drops and Inferred Fault Strength on the Hayward Fault, East San Francisco Bay, California, *Bull. Seism. Soc. Am.*, 99, 1801-1814, 2009.

Pennington, C., X. Chen, R. W. Abercrombie & Q. Wu (2020) Cross Validation of Stress Drop Estimates and Interpretations for the 2011 Prague, OK, Earthquake Sequence Using Multiple Methods, *J Geophys Res: Solid Earth*, submitted.

Ruhl, C. , Abercrombie, R. E., & Shearer, P. M. (2020) Stress variation during the Mogul, Nevada, Earthquake sequence, *in prep.*

Shearer, P. M., R. E. Abercrombie, D. T. Trugman, Wei Wang, Comparing EGF Methods for Estimating Corner Frequency and Stress Drop From P Wave Spectra, *J Geophys Res: Solid Earth*, 10.1029/2018JB016957, **124**, 4, (3966-3986), (2019).

Shearer, P. M., and R. E. Abercrombie (2020) Calibrating Spectral Decomposition of Local Earthquakes using Borehole Seismic Records - Results for the 1992 Big Bear Aftershocks in Southern California, *J Geophys Res: Solid Earth, in revision.*

Trugman, D. T., Dougherty, S. L., Cochran, E. S., & Shearer, P. M. (2017). Source spectral properties of small to moderate earthquakes in southern Kansas. *J Geophys Res: Solid Earth*, 122, 8021-8034. https://doi.org/10.1002/2017JB014649

Trugman, D. T., P. M. Shearer, Strong Correlation between Stress Drop and Peak Ground Acceleration for Recent M 1–4 Earthquakes in the San Francisco Bay Area, *Bull. Seism. Soc. Am.*, 10.1785/0120170245, **108**, 2, (929-945), (2018).

Trugman, D. T. Stress-Drop and Source Scaling of the 2019 Ridgecrest, California, Earthquake Sequence, *Bull. Seism. Soc. Am.*, 10.1785/0120200009, (2020).

Trugman, D. T., & Shearer, P. M. (2017a). Application of an improved spectral decomposition method to examine earthquake source scaling in Southern California. *J Geophys Res: Solid Earth*, **122**, 2890–2910. https://doi.org/10.1002/2017JB013971

Zhang, J., X. Chen and R. E. Abercrombie (2019). Resolving the spatiotemporal variability of small earthquake source parameters at Parkfield and their relationship with 2004 M6 Parkfield earthquake, Abstract S51E-0445 AGU *Fall Meeting.*

General:

Brune, J. (1970), Tectonic stress and the spectra of seismic shear waves from earthquakes, *J. Geophys. Res.*, 75, 4997-5009.

Shearer, P. M., G. A. Prieto, and E. Hauksson (2006), Comprehensive analysis of earthquake source spectra in Southern California, *J. Geophys. Res.*, **111**, B06303, doi:10.1029/2005JB003979.

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