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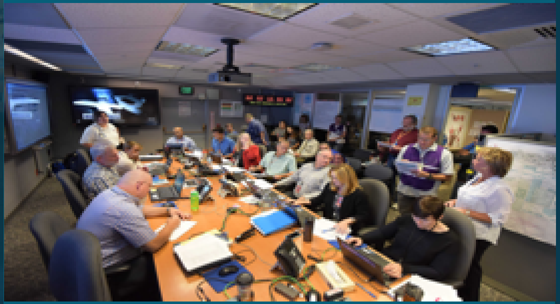
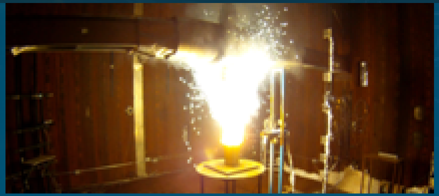
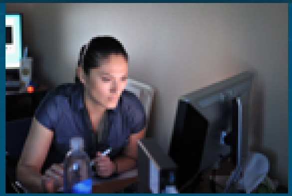
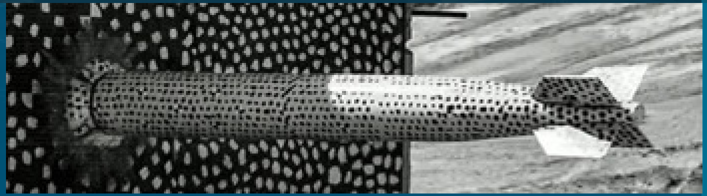
Sandia National Laboratories

Regional Attenuation: An Overview









Presented By

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U.S. DEPARTMENT OF ENERGY NNSA National Nuclear Security Administration

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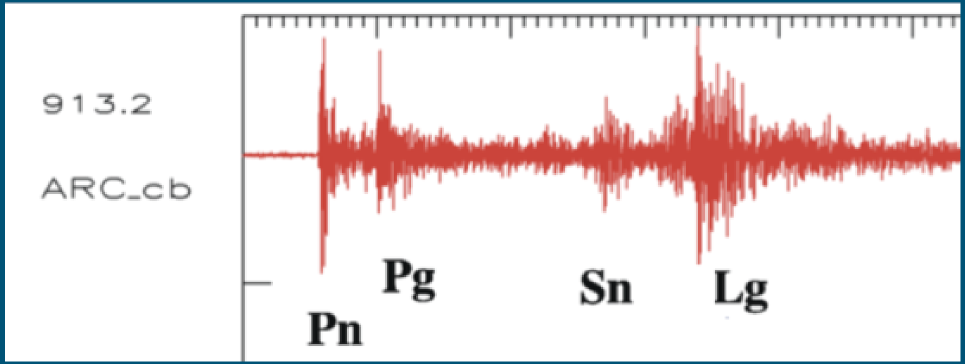
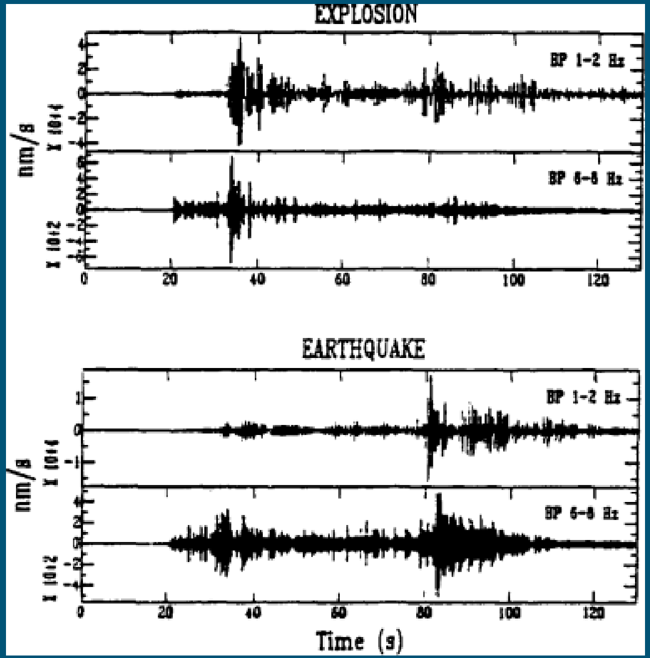
Outline

- What is a regional phase?
- How do we measure regional phase attenuation?
- Quality control
- What causes attenuation?
- How should attenuation be modeled?
- Censored data
- Summary

What is a regional phase?

- Regional phases occur between ~2 and 20 degrees epicentral distance
- The four main phases (**Pn, Pg, Sn, Lg**) are defined by IASPEI as:
  - **Pn** – Any P wave bottoming in the uppermost mantle or an upgoing P wave from a source in the uppermost mantle.
  - **Pg** –At regional distances, an arrival caused by multiple P-wave reverberations inside the whole crust with a group velocity around 5.8 km/s.
  - **Sn** – Any S wave bottoming in the uppermost mantle or an upgoing S wave from a source in the uppermost mantle.
  - **Lg** – A wave group observed at larger regional distances and caused by superposition of multiple S-wave reverberations and SV to P and/or P to SV conversions inside the whole crust. The maximum energy travels with a group velocity around 3.5 km/s.
- Regional phase amplitudes are often used to perform yield estimation and event discrimination (e.g., P/Lg ratios)
  - Regional phase data are often the only data available
- Need to understand regional phase attenuation to accurately perform yield estimation and discrimination

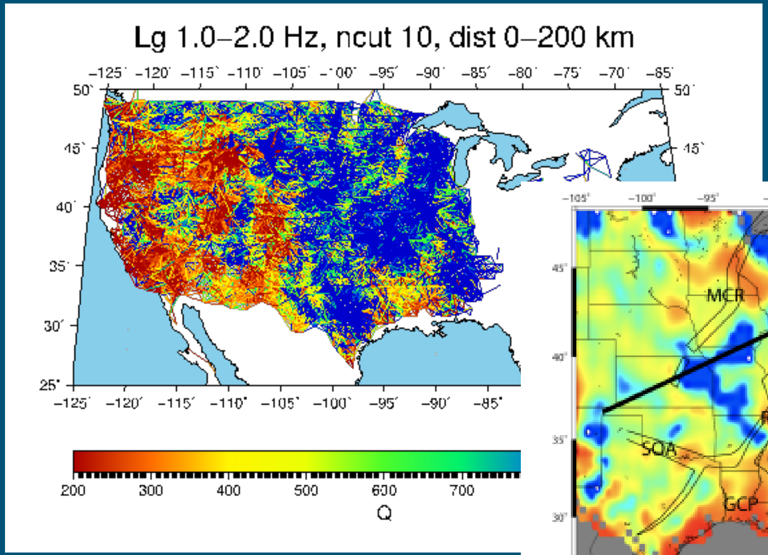




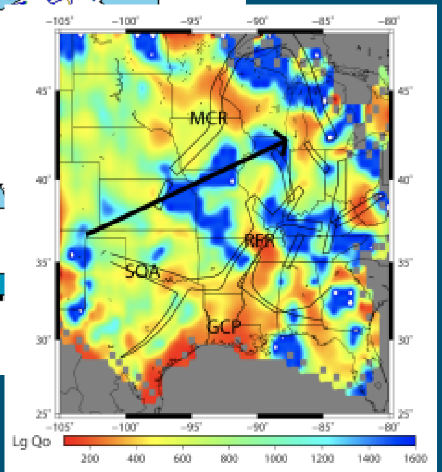
Myers & Wallace (1991)

How do we measure regional phase attenuation?

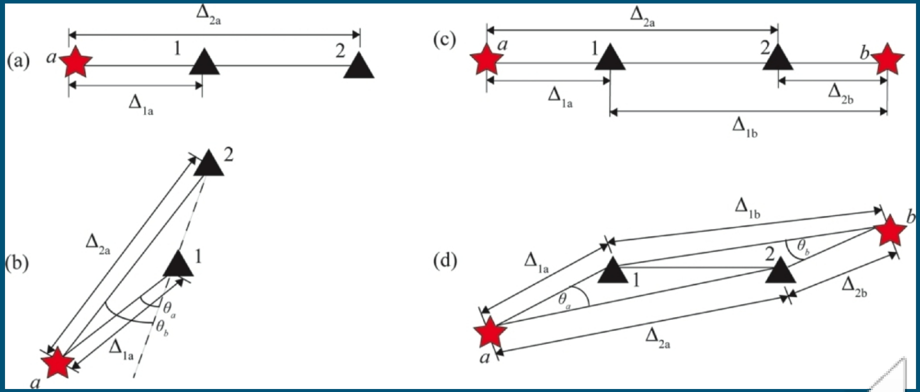
- Attenuation is measured via the unitless quality factor Q
  - Q is a measure of relative energy loss per oscillation cycle
  - Low Q = high attenuation, high Q = low attenuation
  - Q is typically plotted in 2D attenuation tomography maps
  - Can further be divided into intrinsic and scattering Q
- Q is typically inverted for using either two-station (e.g., Gallegos et al., 2014) or single-station (e.g., Phillips et al., 2000) methods
- Two-station methods have the advantage of solving for Q without having to make assumptions about the source or instrument response
  - Disadvantage – Needs dense station distribution to fulfill strict station configuration requirements
- Single station methods have the advantage of being able to be applied anywhere a station exists
  - Disadvantage – Parameters such as source and site parameters must either be simultaneously inverted for (resulting in trade-offs) or assumed. Instrument response must be known



W.S. Phillips (personal communication)

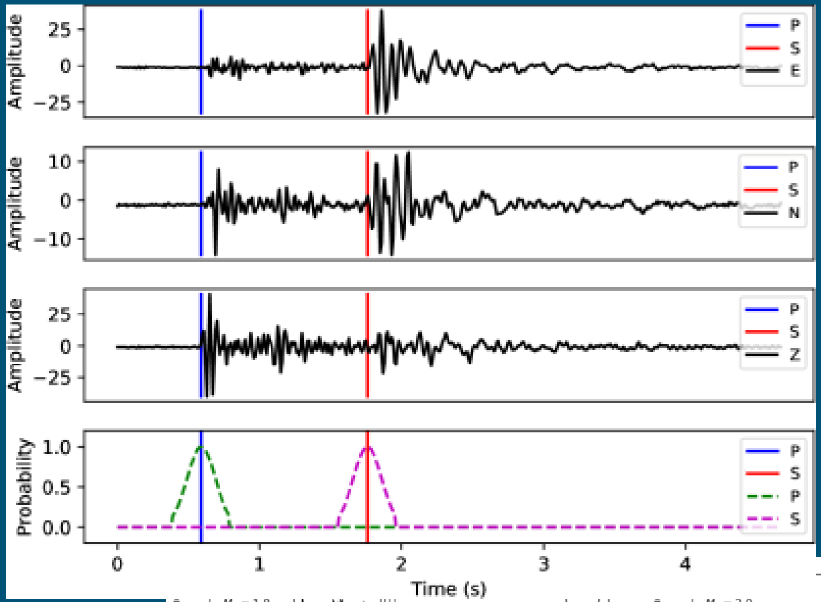


Gallegos et al. (2014)



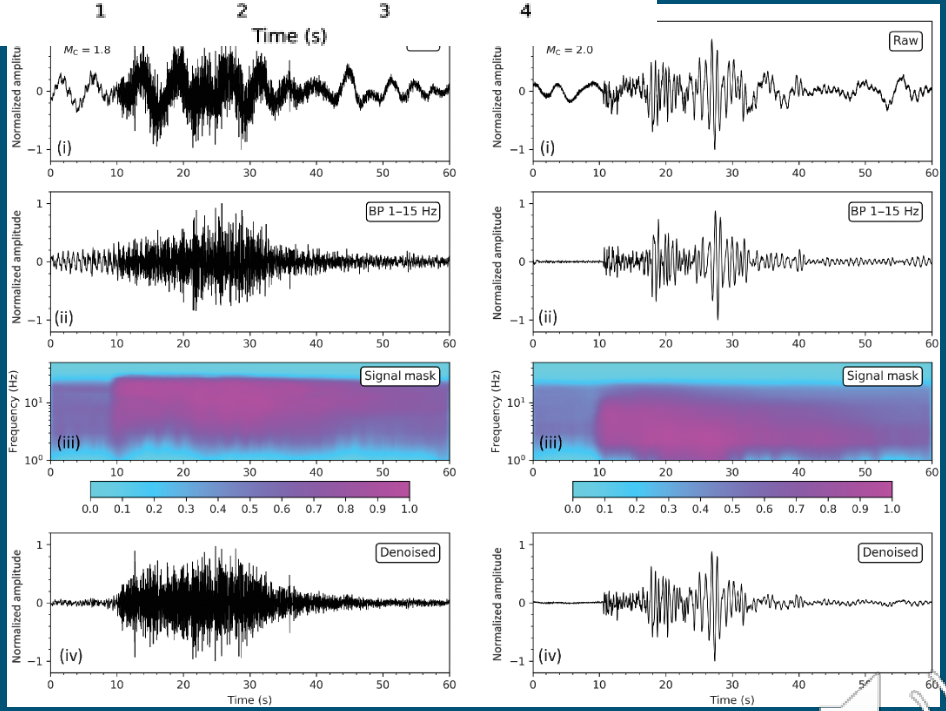
Gallegos et al. (2017)

Quality control



Zhu & Beroza (2018)

- Data quality control plays a large role in generating accurate attenuation tomography models
  - Regional phases can often be highly noisy due to longer epicentral distances exposing them to more earth structure
  - Phases such as Pg and Lg can be highly emergent, making them difficult to accurately pick
  - For single station methods, the instrument response needs to be well-known
- **Question 1:** Can we better automate picking?
- **Question 2:** Can we better deal with removing noise from our data?
- Machine learning methods such as PhaseNet (Zhu & Beroza, 2018) or deep learning denoising (Tibi et al., 2021) may be one avenue



Tibi et al. (2021)

What causes attenuation?

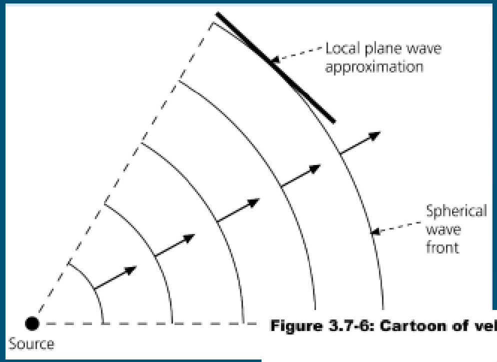
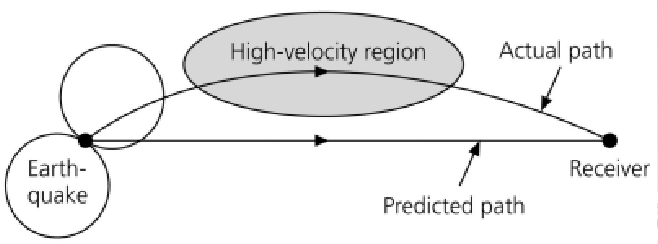


Figure 3.7-6: Cartoon of velocity heterogeneity causing multipathing.



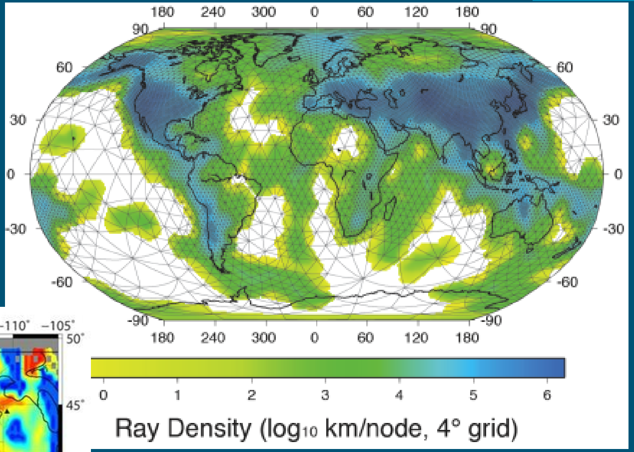
Zhang 2006

- Attenuation has been shown to be affected by a variety of factors, including:
  - Temperature (e.g., Frankel 1991)
  - Crustal age (e.g., Mitchell et al. 1997)
  - Unconsolidated sediments (e.g., Mitchell & Hwang 1987)
  - Extent of deformation (e.g., Pasyanos et al. 2009)
  - Presence of fluids (e.g., Mitchell 1995)
  - Presence of partial melt (e.g., Xie et al. 2004)
- Other factors that effectively cause attenuation included:
  - Geometrical spreading– as the wavefront moves out from the source, energy is spread over an increasing area and amplitude decreases
  - Focusing and defocusing effects caused by multi-pathing
  - Crust is too thin to support reverberations (Lg and Pg specifically)
- **Question 3:** What are the underlying physics behind these different attenuation causes?
  - Which factors are a result of intrinsic Q (water, crustal age, temperature)? Which are caused by scattering Q (unconsolidated sediments, deformation)?
- Understanding the underlying physics is important for extrapolating what Q should be in regions with little or no data

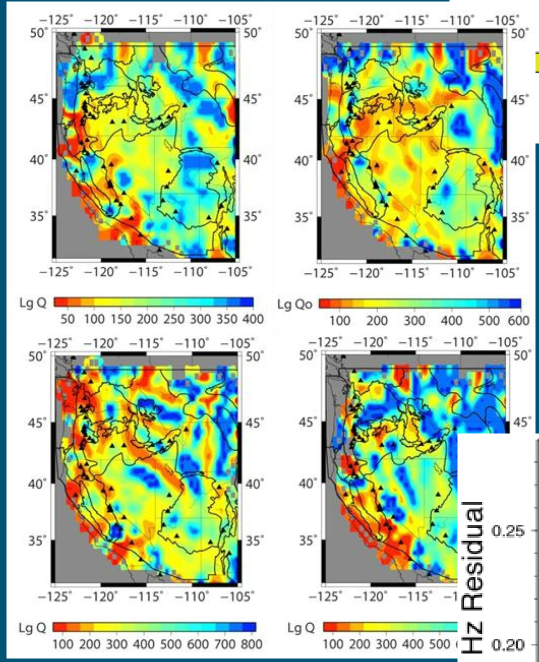
How should attenuation be modeled?

We need accurate attenuation models to estimate accurate yields and have accurate event discrimination. But how exactly should attenuation be modeled? How can we account for effects that mimic attenuation?

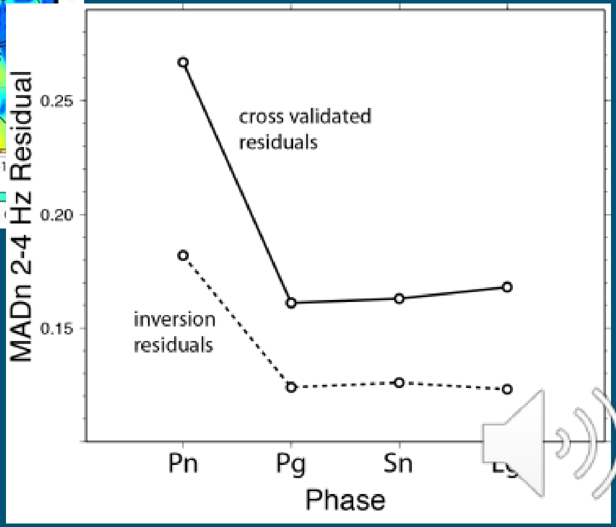
- **Question 4:** How can we model 3D attenuation?
- **Question 5:** Q (f) has empirically been shown to vary with frequency as a power law, $Q(f) = Q_0 (f/f_0)^{\eta}$. Is this true in all cases? What are the underlying physics?
  - Understanding how Q varies with frequency is important since different events will contain different information at different frequencies, e.g., smaller events will be better characterized in higher frequency bands
- **Question 6:** What is the true geometrical spreading of each seismic phase?
  - Studies such as Yang (2002) and Fisk & Phillips (2013) have attempted to answer this question
  - The Fisk & Phillips (2013) study indicates that the typically used factor for Pn may not be correct at far regional distances. In fact Pn data have been shown to poorly fit 2D Q models
  - Yang (2007, 2011) also found Pn spreading to differ from more standard models



W.S. Phillips (personal communication)



Gallegos et al. (2017)



W.S. Phillips (personal

Censored data

- In some regions, the regional phases we rely on to perform yield estimation and event discrimination are blocked due to path effects.
- These regions can be considered areas of "left-censored" data, i.e., regions where the phase amplitude data are lower than the background SNR
- These regions will correspond with regions of low Q in attenuation models (e.g., Tibet for Lg).
- **Question 7:** Can we predict where blockage will occur?
  - Sandvol et al. (2020) proposed using a Bayesian Lasso method to predict the likelihood of blockage, for instance
- **Question 8:** How can we accurately estimate Q, and thereby amplitude, in regions with blockage?
  - Sandvol et al. (2018) showed that including amplitude reduction data inferred from censored data along with more typically observed amplitude data improved Sn Q models

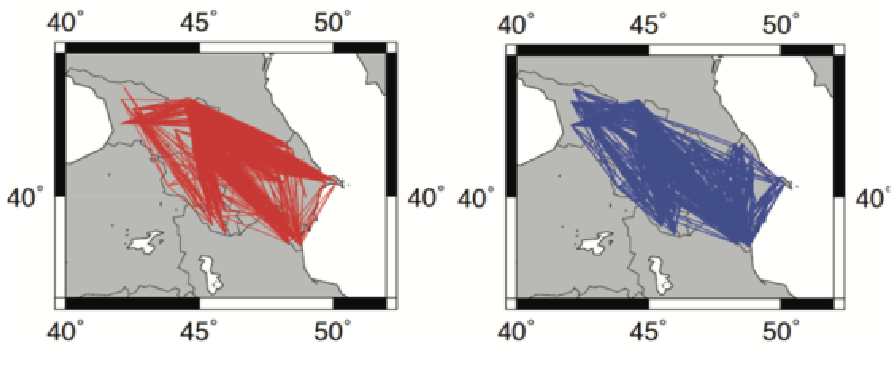
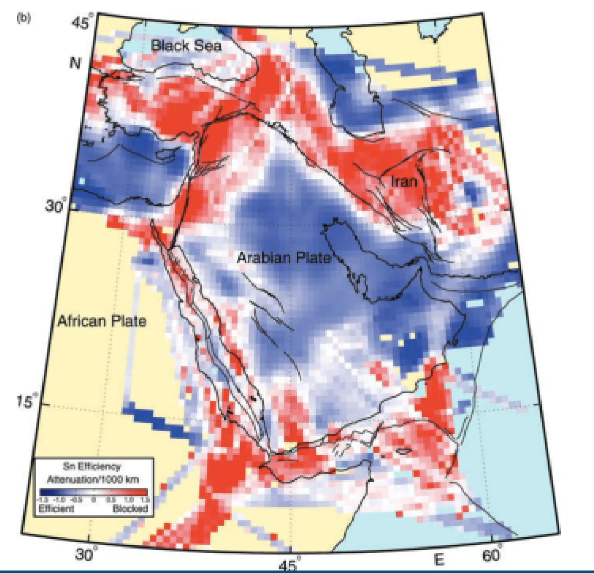


Figure 14. (Left; red) Blocked paths. (Right; blue) Efficient paths. *Note the similarity in paths.*

Sandvol et al. (2020)



Al-Damegh et al. (2004)

Summary

- Attenuation of regional phases (Pn, Pg, Sn, Lg) is a vital area of study in nuclear monitoring, particularly for accurate yield estimation and event discrimination
- Although much progress has been made, several questions remain open to study, including but not limited to:
  - How can we better automate and improve data processing to both improve our models and free up researcher time?
  - What are the underlying physics of attenuation? Can we separate intrinsic attenuation from scattering attenuation?
  - How can we retrieve Q in 3D?
  - Is there a physical reasoning underlying the Q power law? Is the power law the best way to model attenuation varying with frequency?
  - What are the correct geometrical spreading factors for regional seismic phases?
  - Can we accurately determine where data censoring (i.e., blockage) will cause issues in amplitude estimation? Can we remove our bias towards higher Q maps by adding in data underlying censored data?