Characterizing Outburst with Microseismic Amplitude Versus Angle Analysis

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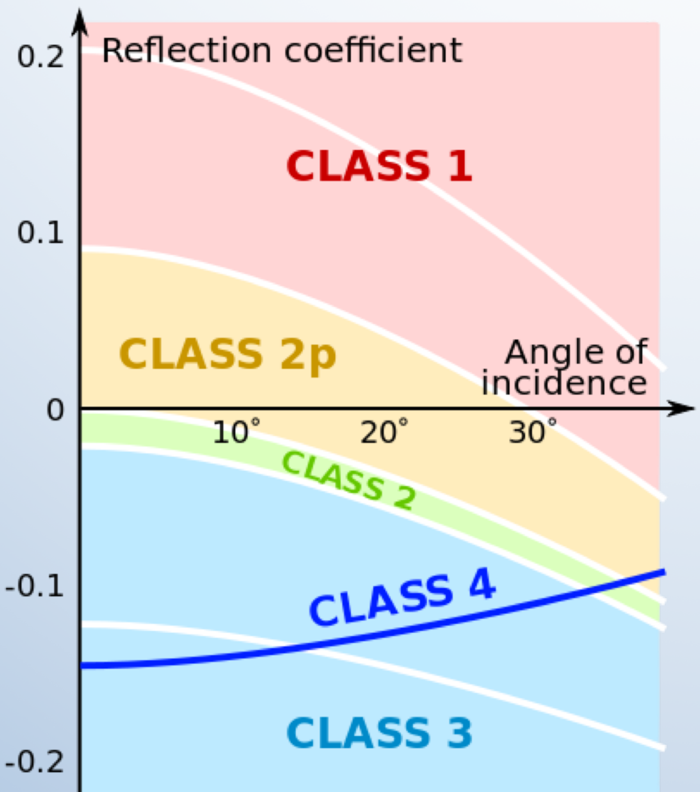
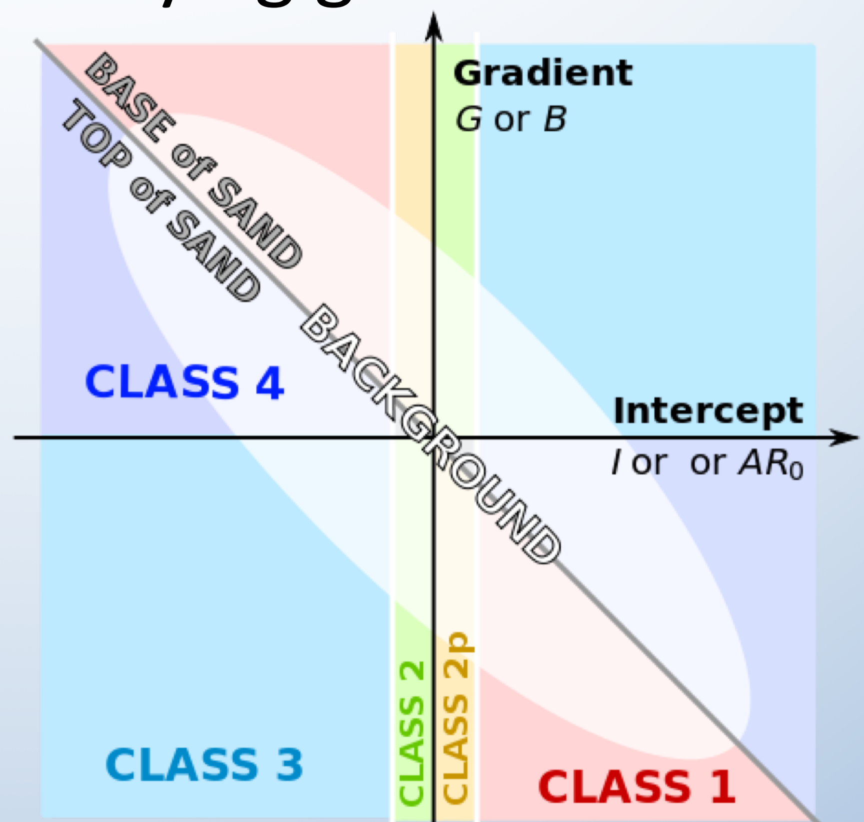
Introduction

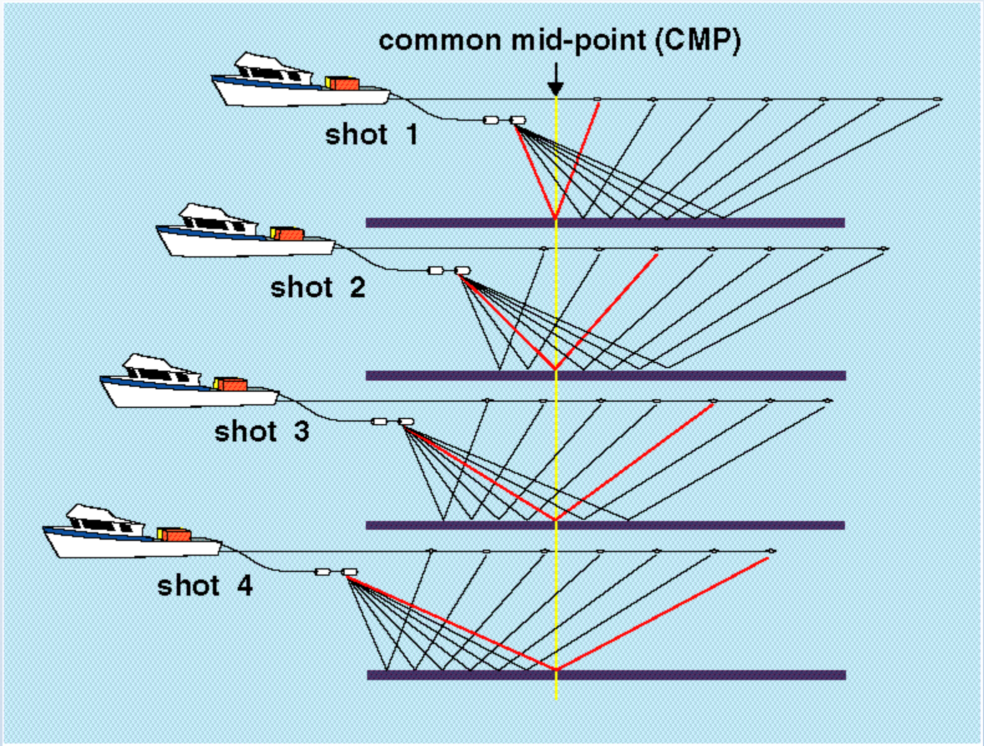
- Amplitude Variation with Offset/Angle (AVO/AVA) analysis is a popular technique with seismic surveys for classifying gas reservoirs





Objective

- Can MS amplitude variation with angle separating sensor from source (rockburst or gas outburst) give us information about the hazardous layer?
- Can the reflection-based methods be translated for transmission waves?



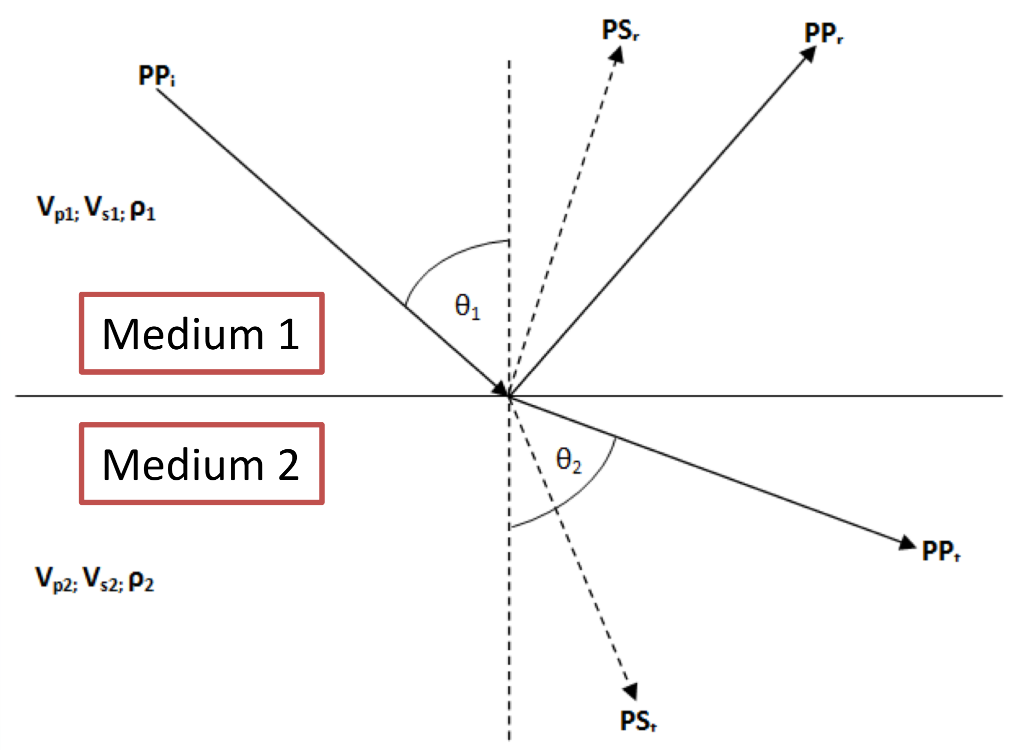
Simplification of Zoeppritz Equations

Reflection Coefficient:

$$R_{12} = \frac{A_r}{A_i} = \frac{I_1 - I_2}{I_2 + I_1} = \frac{\rho_1 V_1 - \rho_2 V_2}{\rho_2 V_2 + \rho_1 V_1}$$

Transmission Coefficient:

$$T_{12} = \frac{A_t}{A_i} = \frac{2I_1}{I_2 + I_1} = \frac{2\rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$



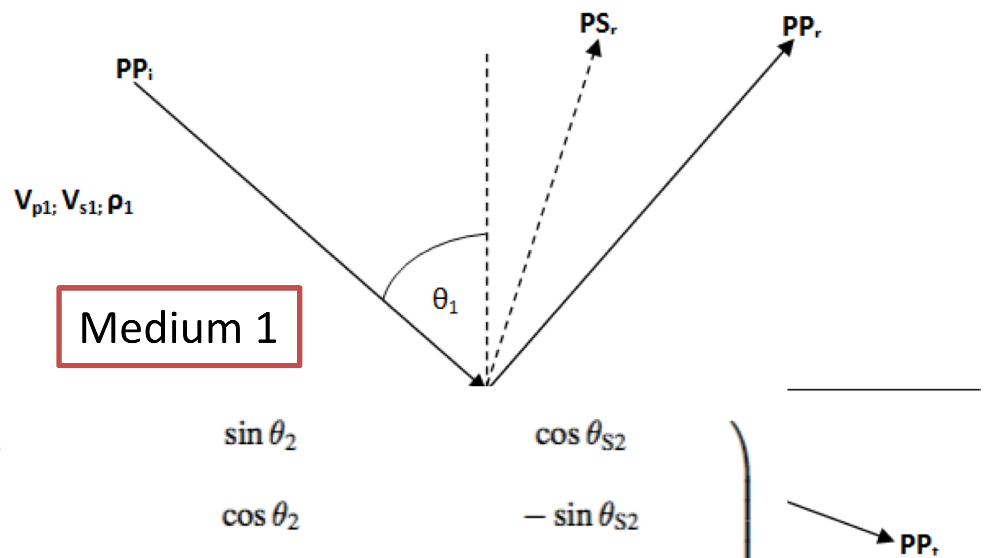
Ray Parameter (Snell's Law):

$$p = \frac{\sin\theta_1}{V_{P1}} = \frac{\sin\theta_2}{V_{P2}} = \frac{\sin\theta_{S1}}{V_{S1}} = \frac{\sin\theta_{S2}}{V_{S2}}$$

Aki, K. and Richards, P.G., 1980. Quantitative Seismology: Theory and Methods. San Francisco, CA: W. H. Freeman and Co.

Simplification of Zoeppritz Equations

$$\begin{pmatrix} \overset{\downarrow\uparrow}{PP} & \overset{\downarrow\uparrow}{SP} & \overset{\uparrow\uparrow}{PP} & \overset{\uparrow\uparrow}{SP} \\ \overset{\downarrow\uparrow}{PS} & \overset{\downarrow\uparrow}{SS} & \overset{\uparrow\uparrow}{PS} & \overset{\uparrow\uparrow}{SS} \\ \overset{\downarrow\downarrow}{PP} & \overset{\downarrow\downarrow}{SP} & \overset{\uparrow\downarrow}{PP} & \overset{\uparrow\downarrow}{SP} \\ \overset{\downarrow\downarrow}{PS} & & & \end{pmatrix} = \mathbf{M}^{-1}\mathbf{N}$$



$$\mathbf{M} = \begin{pmatrix} -\sin\theta_1 & -\cos\theta_{S1} & \sin\theta_2 & \cos\theta_{S2} \\ \cos\theta_1 & -\sin\theta_{S1} & \cos\theta_2 & -\sin\theta_{S2} \\ 2\rho_1 V_{S1}\sin\theta_{S1}\cos\theta_1 & \rho_1 V_{S1}\left(1-2\sin^2\theta_{S1}\right) & 2\rho_2 V_{S2}\sin\theta_{S2}\cos\theta_2 & \rho_2 V_{S2}\left(1-2\sin^2\theta_{S2}\right) \\ -\rho_1 V_{P1}\left(1-2\sin^2\theta_{S1}\right) & \rho_1 V_{S1}\sin 2\theta_{S1} & \rho_2 V_{P2}\left(1-2\sin^2\theta_{S2}\right) & -\rho_2 V_{S2}\sin 2\theta_{S2} \end{pmatrix}$$

$$\mathbf{N} = \begin{pmatrix} \sin\theta_1 & \cos\theta_{S1} & -\sin\theta_2 & -\cos\theta_{S2} \\ \cos\theta_1 & -\sin\theta_{S1} & \cos\theta_2 & -\sin\theta_{S2} \\ 2\rho_1 V_{S1}\sin\theta_{S1}\cos\theta_1 & \rho_1 V_{S1}\left(1-2\sin^2\theta_{S1}\right) & 2\rho_2 V_{S2}\sin\theta_{S2}\cos\theta_2 & \rho_2 V_{S2}\left(1-2\sin^2\theta_{S2}\right) \\ \rho_1 V_{P1}\left(1-2\sin^2\theta_{S1}\right) & -\rho_1 V_{S1}\sin 2\theta_{S1} & -\rho_2 V_{P2}\left(1-2\sin^2\theta_{S2}\right) & \rho_2 V_{S2}\sin 2\theta_{S2} \end{pmatrix}$$

Aki, K. and … CA: W. H. Freeman and Co.

Shuey's Approximation

$$R(\theta) \approx R(0) + G\sin^2\theta$$

$$\theta = (\theta_1 + \theta_2)/2 \approx \theta_1$$

$$R(0) = \frac{1}{2}\left(\frac{\Delta V_p}{V_p} + \frac{\Delta\rho}{\rho}\right)$$

$$G = \frac{1}{2}\frac{\Delta V_p}{V_p} - 2\frac{V_s^2}{V_p^2}\left(\frac{\Delta\rho}{\rho} + 2\frac{\Delta V_s}{V_s}\right)$$

$$= R(0) - \frac{\Delta\rho}{\rho}\left(\frac{1}{2} + 2\frac{V_s^2}{V_p^2}\right) - 4\frac{V_s^2}{V_p^2}\frac{\Delta V_s}{V_s}$$

$$\Delta\rho = \rho_2 - \rho_1 \qquad \rho = (\rho_2 + \rho_1)/2$$

$$\Delta V_p = V_{p2} - V_{p1} \qquad V_p = (V_{p2} + V_{p1})/2$$

$$\Delta V_s = V_{s2} - V_{s1} \qquad V_s = (V_{s2} + V_{s1})/2$$

Normal-incidence reflection coefficient:
- controlled by impedance contrast

Reflection at intermediate angles between normal and critical angle:
- controlled by impedance & Poisson's ratio

This linear relationship is typically fit via Least Squares

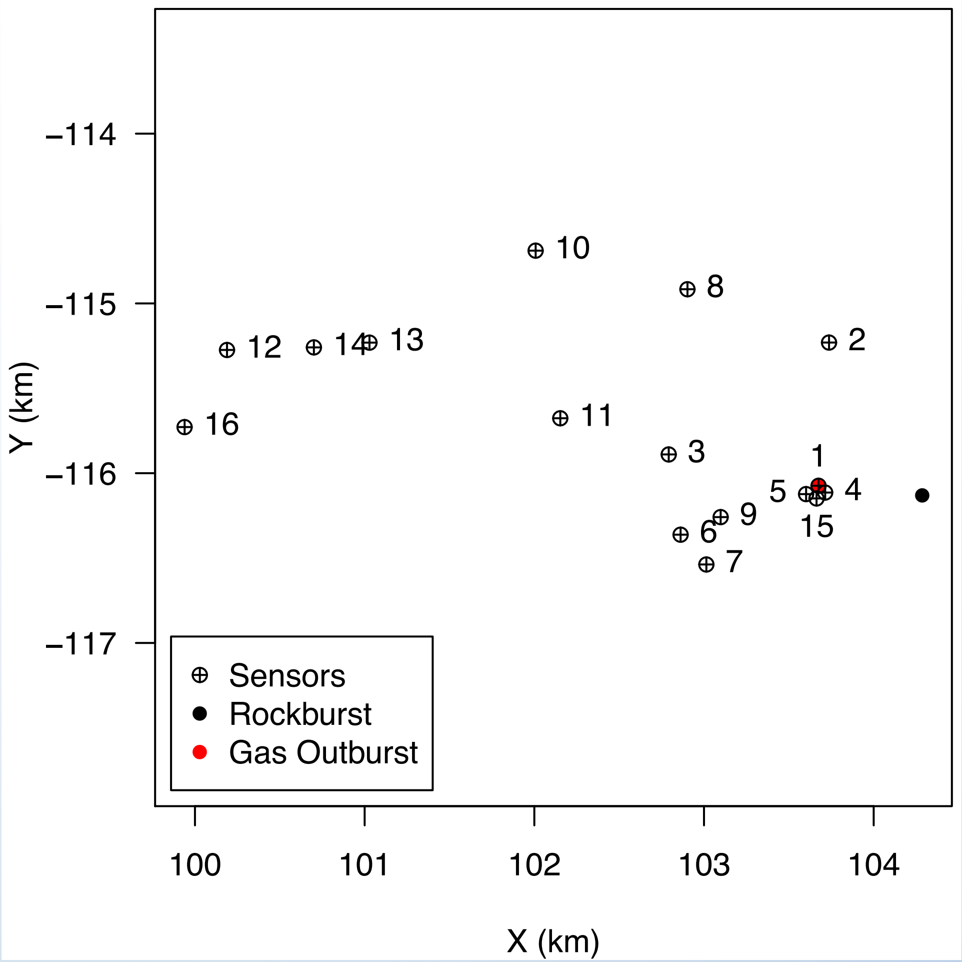
SHUEY, R. T. A Simplification of the Zoeppritz Equations. *Geophysics* **50,** 609–614 (1985).

For Transmitted P-Wave...

$$
\begin{aligned}
T(\theta) &= 1 - \frac{1}{2}\frac{\Delta\rho}{\rho} + \left(\frac{1}{2\cos^2\theta} - 1\right)\frac{\Delta V_p}{V_p} \\
&= 1 - \left[\frac{1}{2}\left(\frac{\Delta\rho}{\rho} + \frac{\Delta V_p}{V_p}\right)\right] + \frac{1}{2}\frac{\Delta V_p}{V_p}\left(\frac{1}{\cos^2\theta} - 1\right) \\
&\approx \underbrace{\frac{2I_1}{I_2 + I_1}}_{\text{Intercept}} + \underbrace{\frac{V_{p2} - V_{p1}}{V_{p2} + V_{p1}}}_{\text{Slope}}\underbrace{\left(\frac{1}{\cos^2\theta} - 1\right)}_{\text{Independent Variable}}
\end{aligned}
$$

MS Dataset

- 16 MS Sensors placed in mine
- Junde coal mine, Nov 24, 2012:
  - Rockburst at 18:24
  - Gas outburst at 20:28

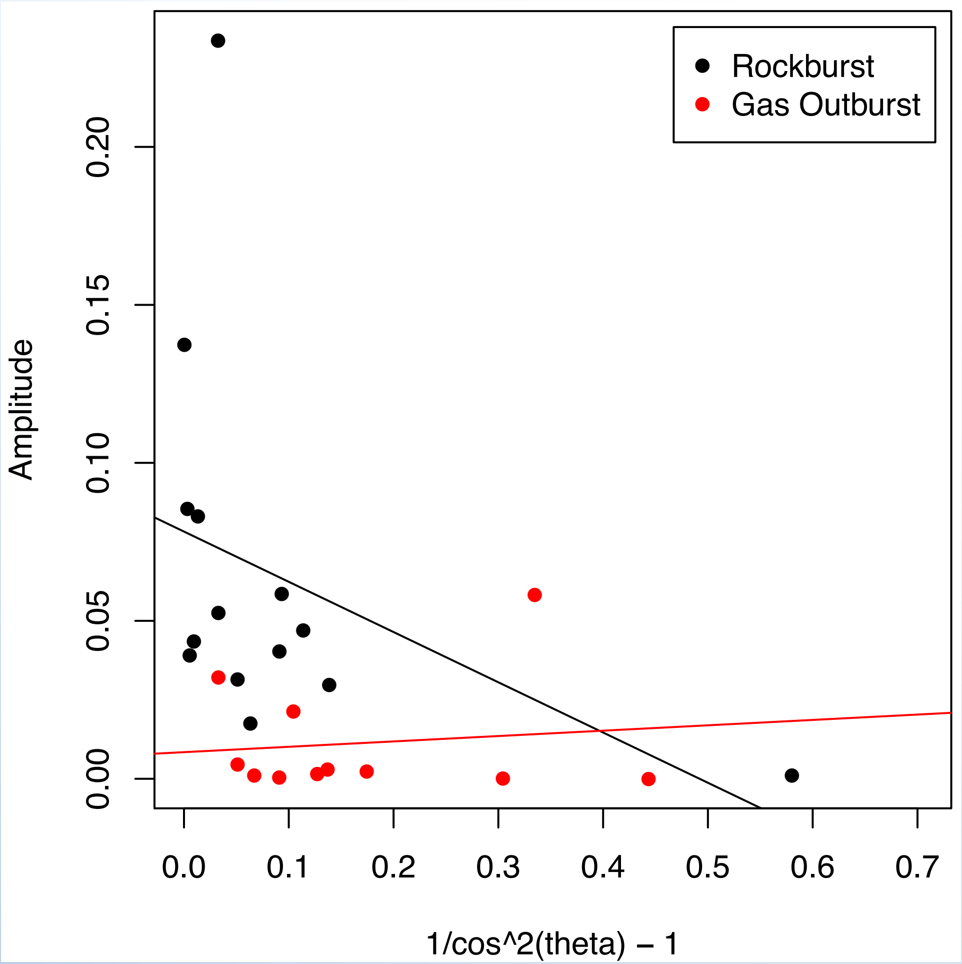


Lu, C.-P., Dou, L.-M., Zhang, N., Xue, J.-H., & Liu, G.-J. (2014). Microseismic and acoustic emission effect on gas outburst hazard triggered by shock wave: a case study. *Natural Hazards*, *73*(3), 1715–1731. doi:10.1007/s11069-014-1167-7

Some Assumptions

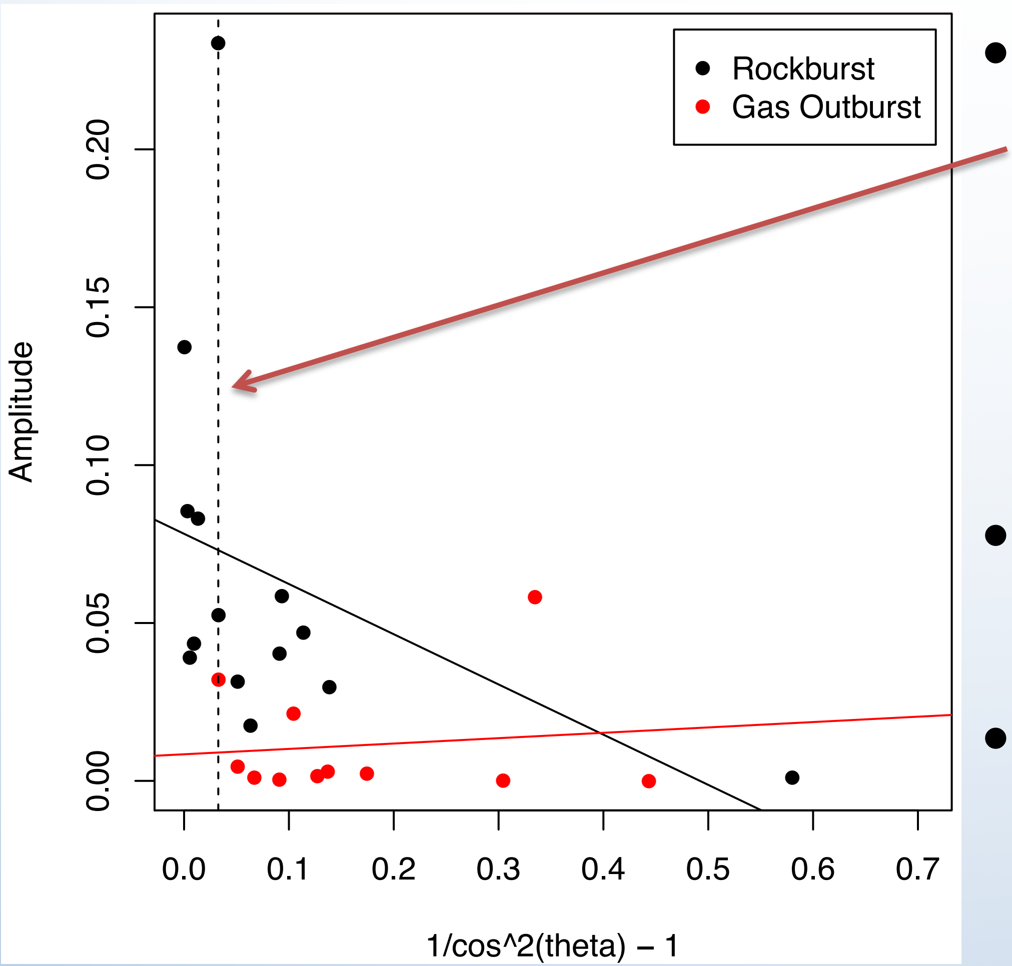
- Max. amplitude is associated with transmitted P-wave
- Coal and surrounding rock are each homogeneous and isotropic
- Critical angle = 40°: sensors outside of this omitted
- Variation in angle with respect to vertical direction is negligible
- Spherical divergence correction

Peak Amplitude vs. Angle



- Rockburst:
  - Significant negative slope:
    - Vp of rockburst layer greater than Vp of surrounding rock
  - Larger intercept:
    - Greater impedance of rockburst layer
- Gas outburst:
  - Slight positive slope
    - Slightly greater Vp of surrounding rock
  - Small intercept
    - Gas outburst in lower impedance layer

Directivity



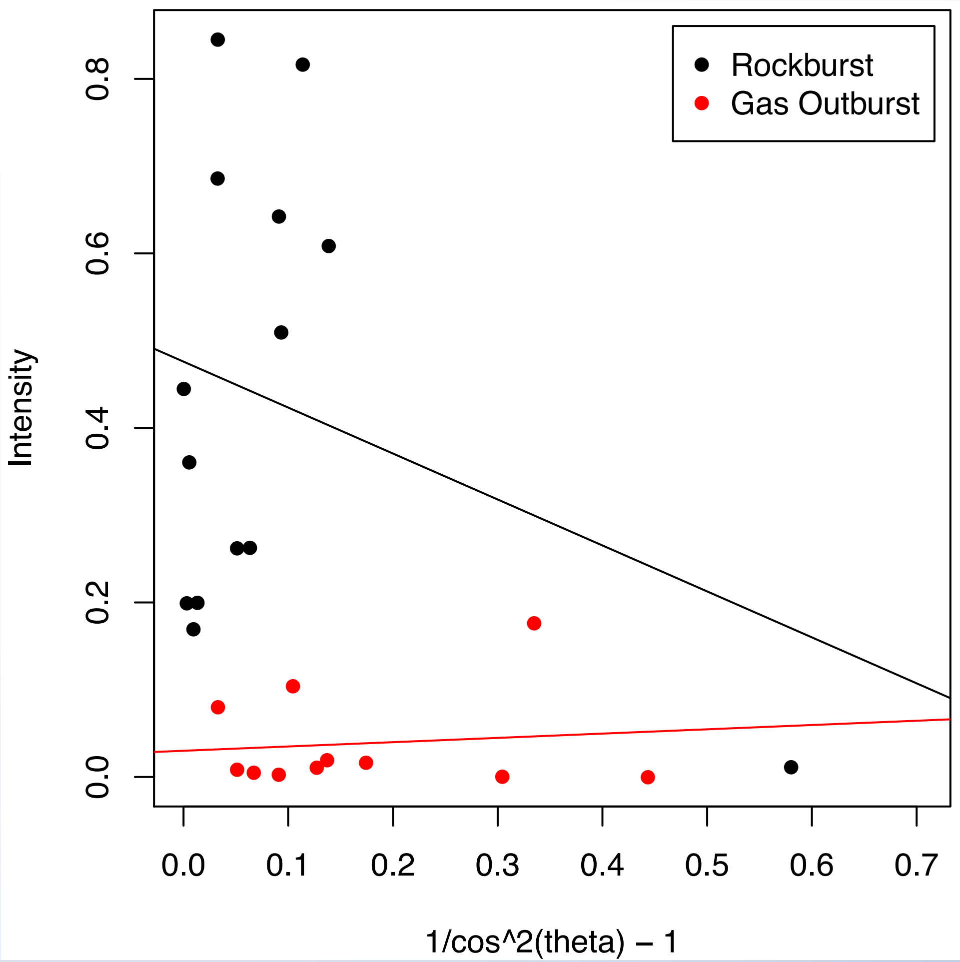
- Angle of gas outburst source from rockburstsource coincides with largest rockburst amplitude
- Rockburst directs energy coaxially
- Gas outburst is isotropic

Intensity

- Calculated as:

$$\int_{0.1\ \mathrm{Hz}}^{250\ \mathrm{Hz}} A(f)df$$

- Implies same directivity effect



Conclusions

- Can simplify Zoeppritz equations to get transmission coefficient in linear form
  - Angle in independent variable
  - Slope is function of Vp
  - Intercept is function of Vp and density (impedance)
- AVA analysis can tell us properties of rock/gas outburst layers
  - Measure angle between MS sensors and sources
  - Pick amplitude from MS time series
- Directivity effect in rockburst may inform about location of gas outburst in future
  - Gives an indication of redistributed stresses

Thank you! XÌe XÌe!

Questions?