Precise Estimation of Elastic Moduli from Sonic Log Data in a Gas Shale Formation

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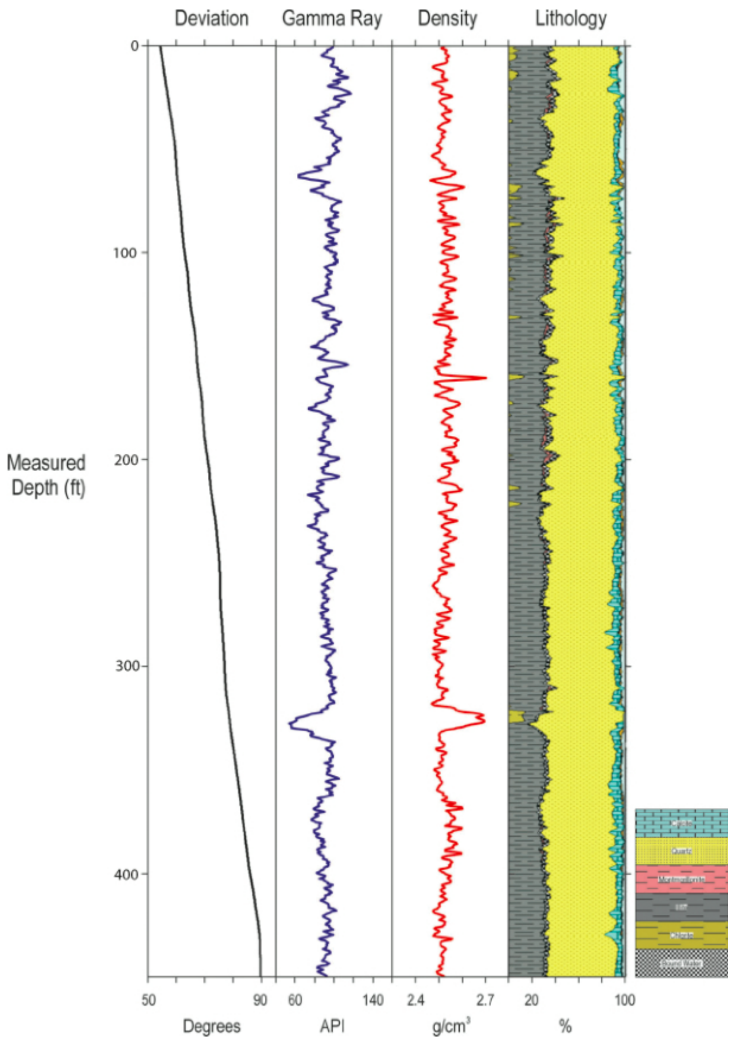
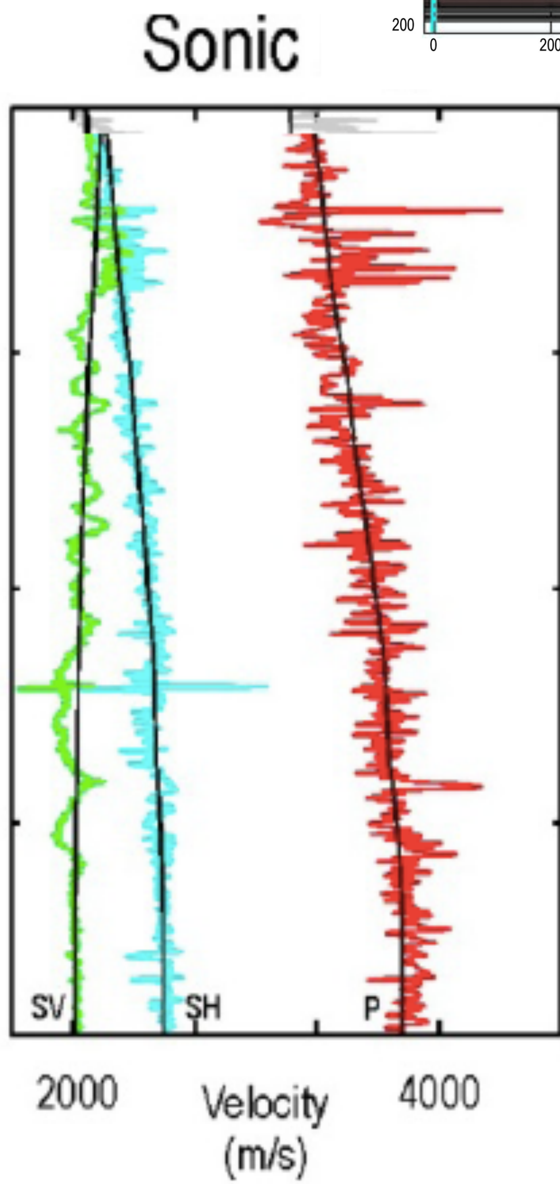
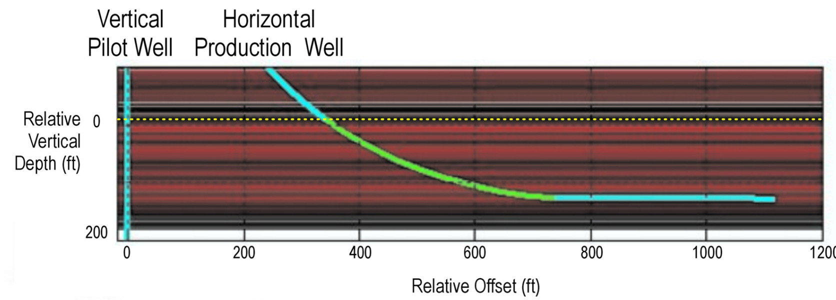
Log Data from a Gas Shale







- Standard dipole sonic acquisition & STC processing
- Sonic data are from build section of deviated well
- 63% quartz; 35% clay; 2% calcite

Miller, Horne, Walsh, 1IWRP August 2011

Fit by a Single TI Model

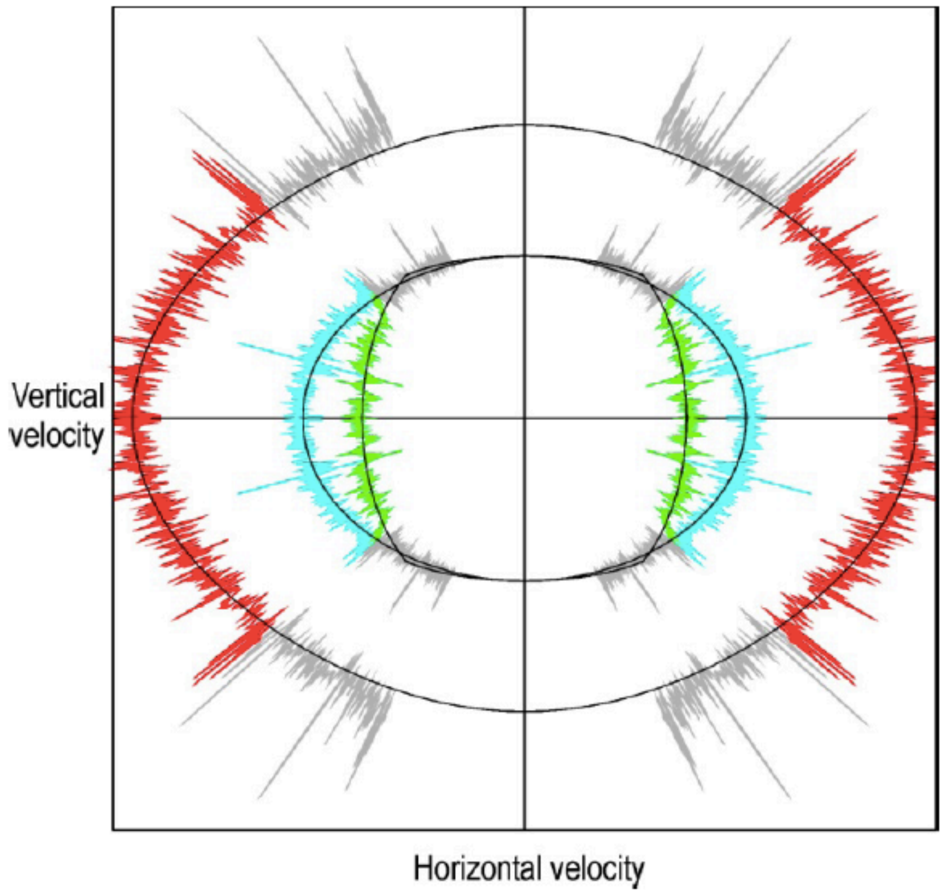


Figure 7. Dipole sonic log data shown in a polar velocity representation. Compressional data are shown in red and the fast and slow shear waves are in blue and green, respectively. Grey lines show data that lie outside the Shale. Overlain on this plot are the modeled velocity curves (black) for the best-fitting anisotropic model. Note that only data in one quadrant is actually acquired, the remaining three quadrants are shown for visual clarity and are generated based on symmetry assumptions.

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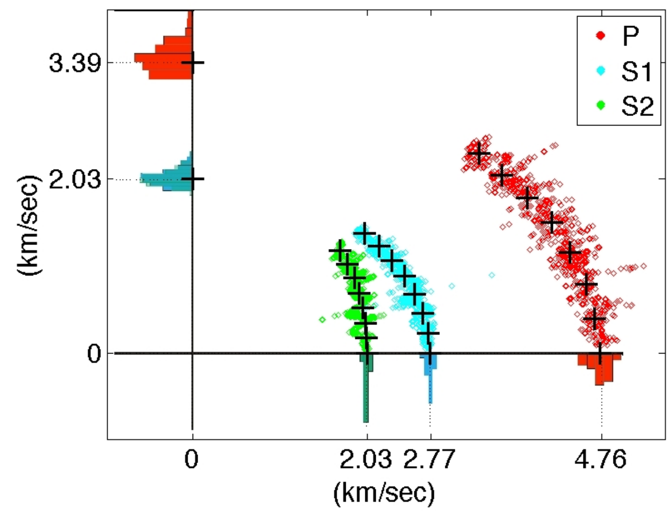
Today's Discussion

- ❑ Some background on anisotropy:
  - ▪ Phase, group, etc

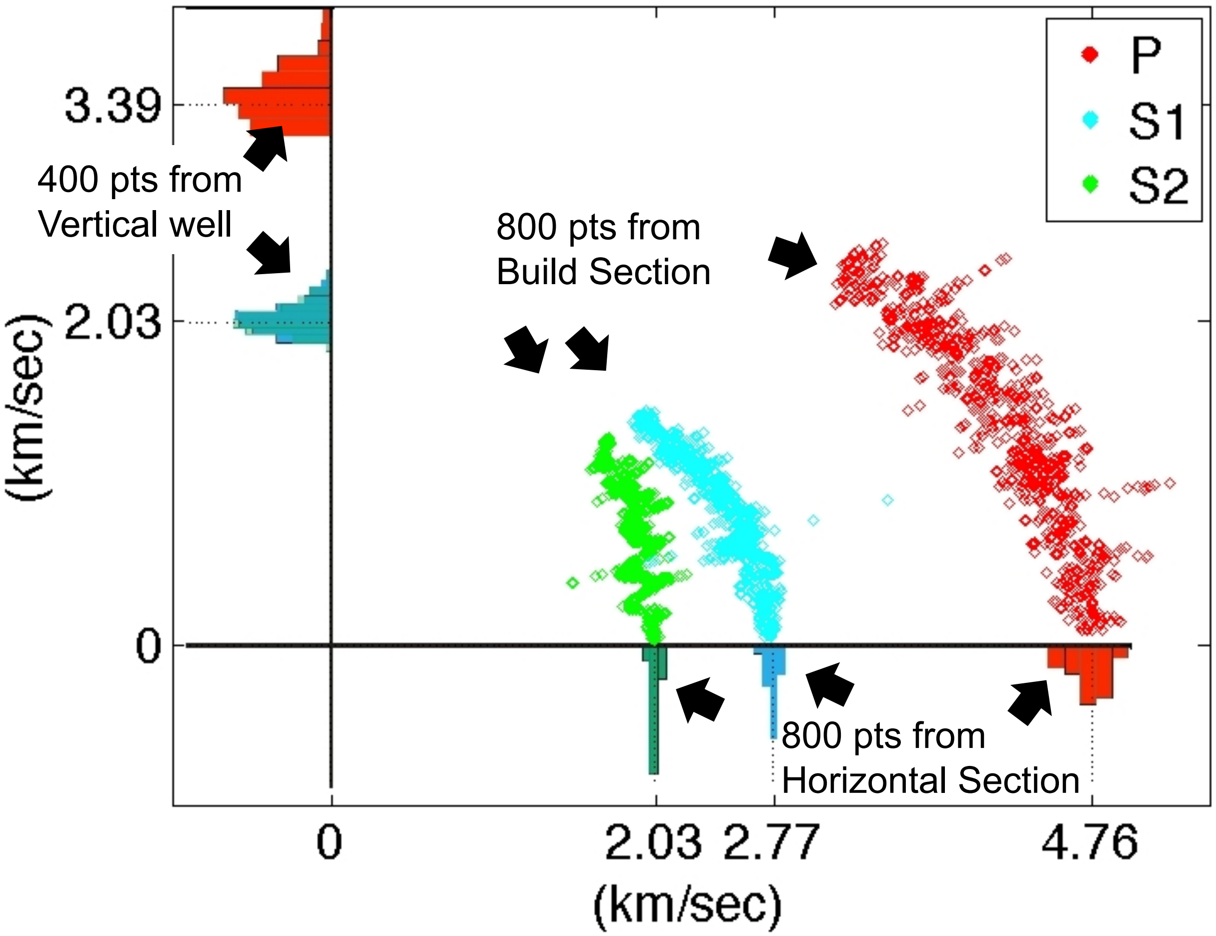
- ❑ The Field Data
  - • Axial Moduli
  - • C13 and the Correspondence Rules
  - • Annie & other misfits

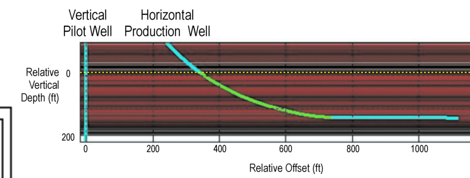


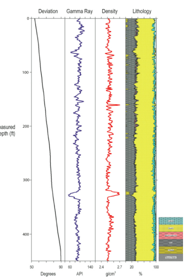
- ❑ The synthetic data & associated processing

- ❑ Concluding remarks

Sonic Log Data from a Gas Shale







- Standard dipole sonic acquisition & STC processing
- Data from axial sections are summarized by histograms
- Data from build section are plotted at borehole inclination angle
- TI anisotropy, lateral and vertical homogeneity are evident from axial data

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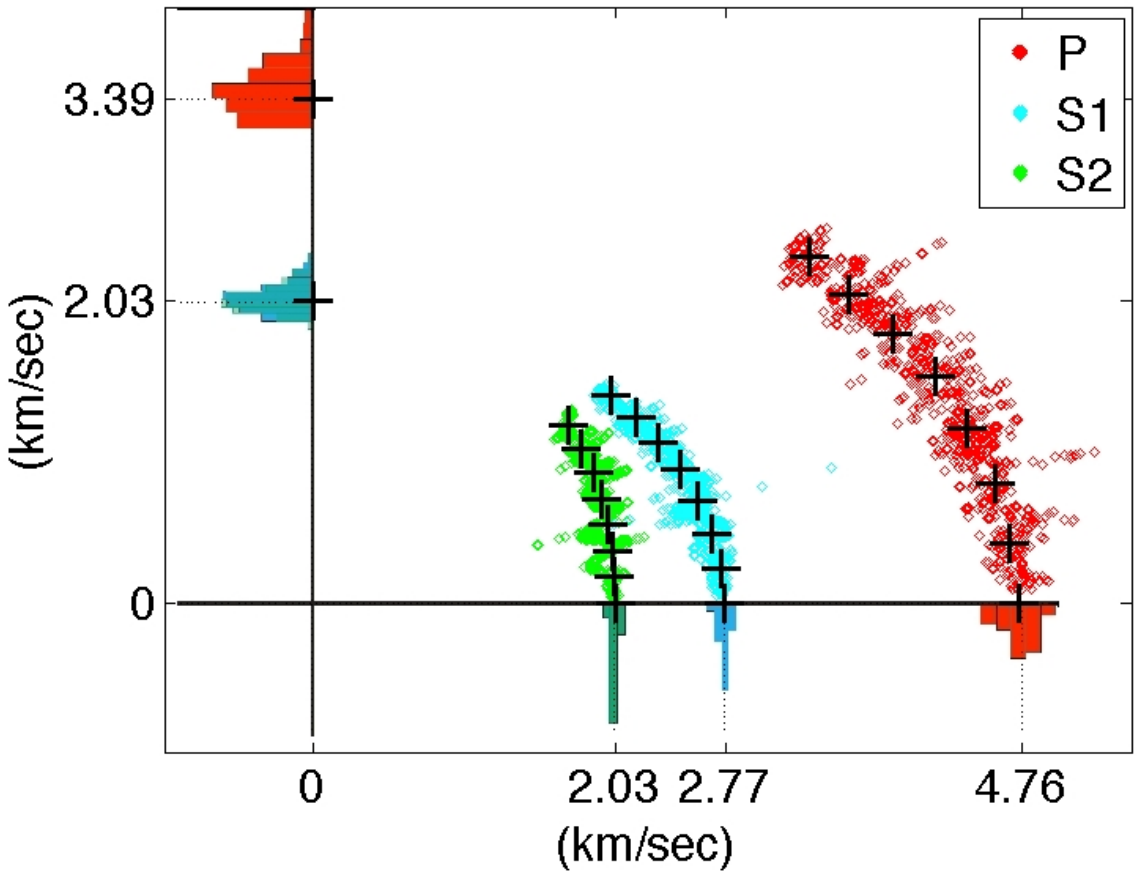
Fit by a Single TI Model



- 3DFD synthetics were created for 9 borehole orientations and 3 modes, then processed with STC

+ Processed 3DFD are plotted at borehole inclination angle

- That's 9000 data points fit with 5 parameters

- We'll describe how the model was obtained, and why it is of particular interest (beyond being a remarkable example of a match between data, *in situ,* and model).

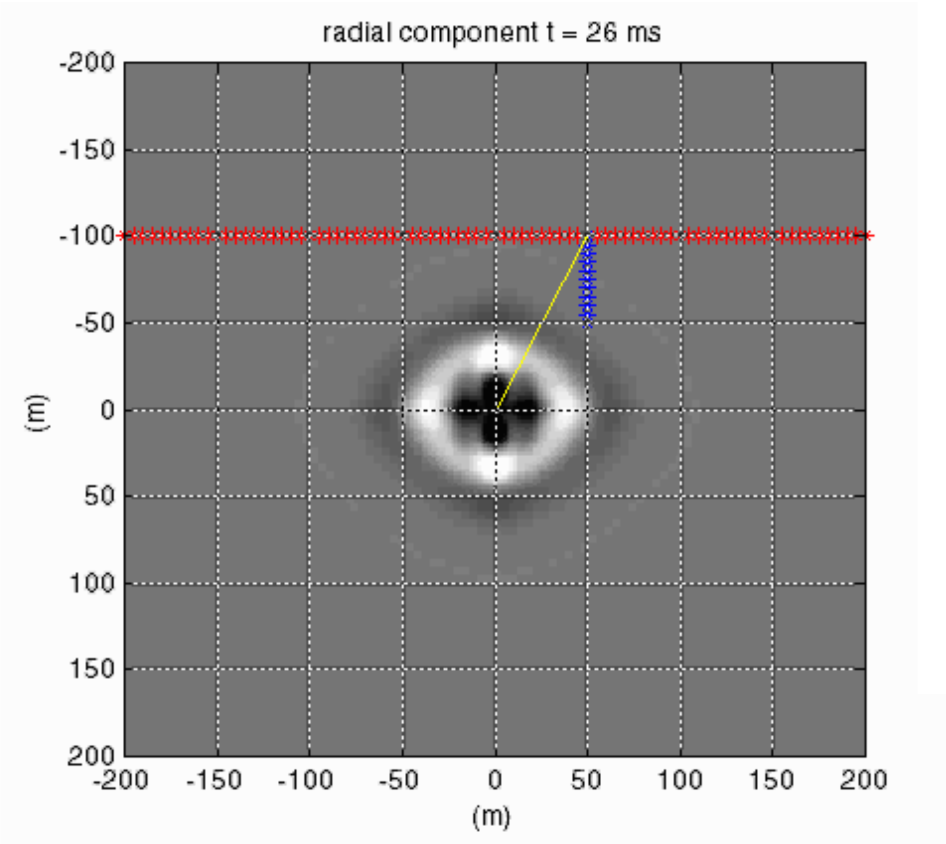
An Important Point

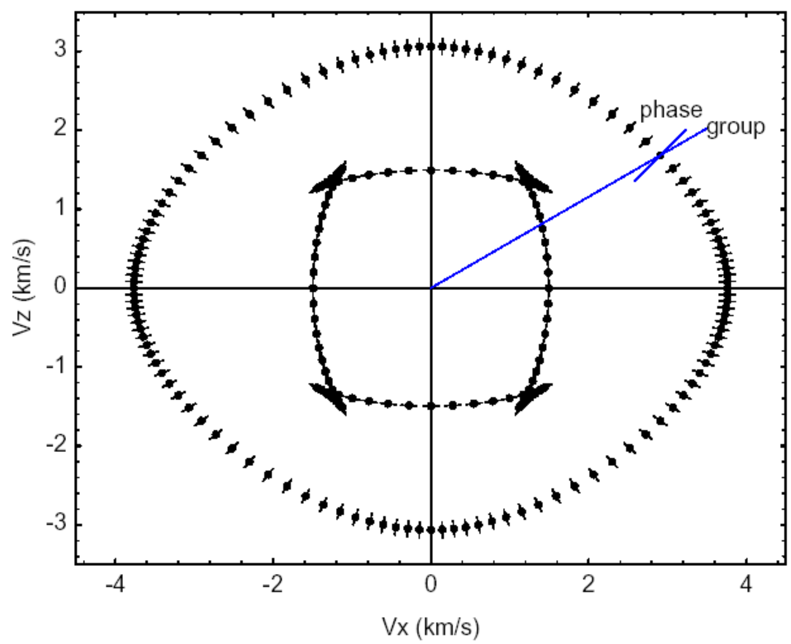
• There has been confusion in the literature regarding interpretation of sonic logs in deviated wells in anisotropic media. Because wavefronts radiated from a point source are not generally spherical, there has been uncertainty about whether borehole inclination should be matched to ray direction (group angle) or wavefront normal direction (phase angle).

Our data clearly show that, at least for fast anisotropic formations such as this gas shale, sonic logs measure **group slowness** for propagation with the **group angle equal to the borehole inclination angle**. The data are inconsistent with an interpretation that they measure phase slownesses for propagation with phase angle equal to borehole inclination angle.

The confusion in the literature stemmed from a failure to properly distinguish group slowness as a function of **group angle** from group slowness as a function of **phase angle**.

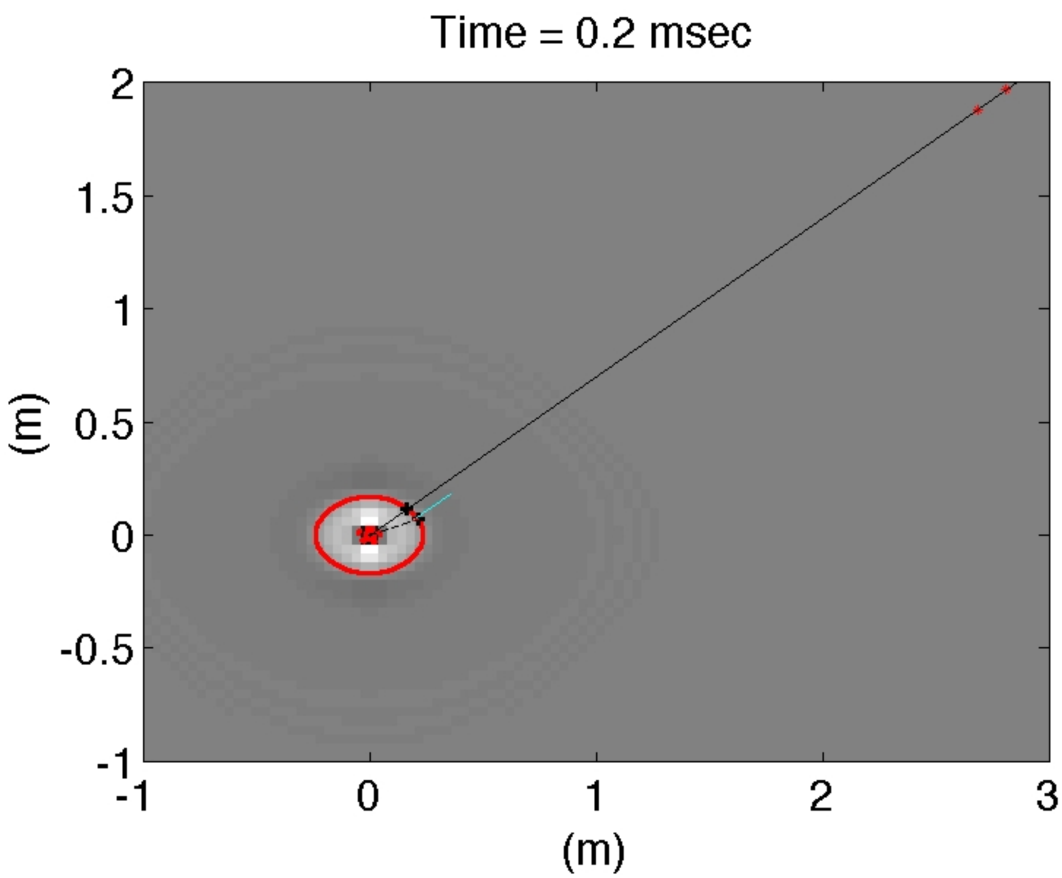
Phase and Group





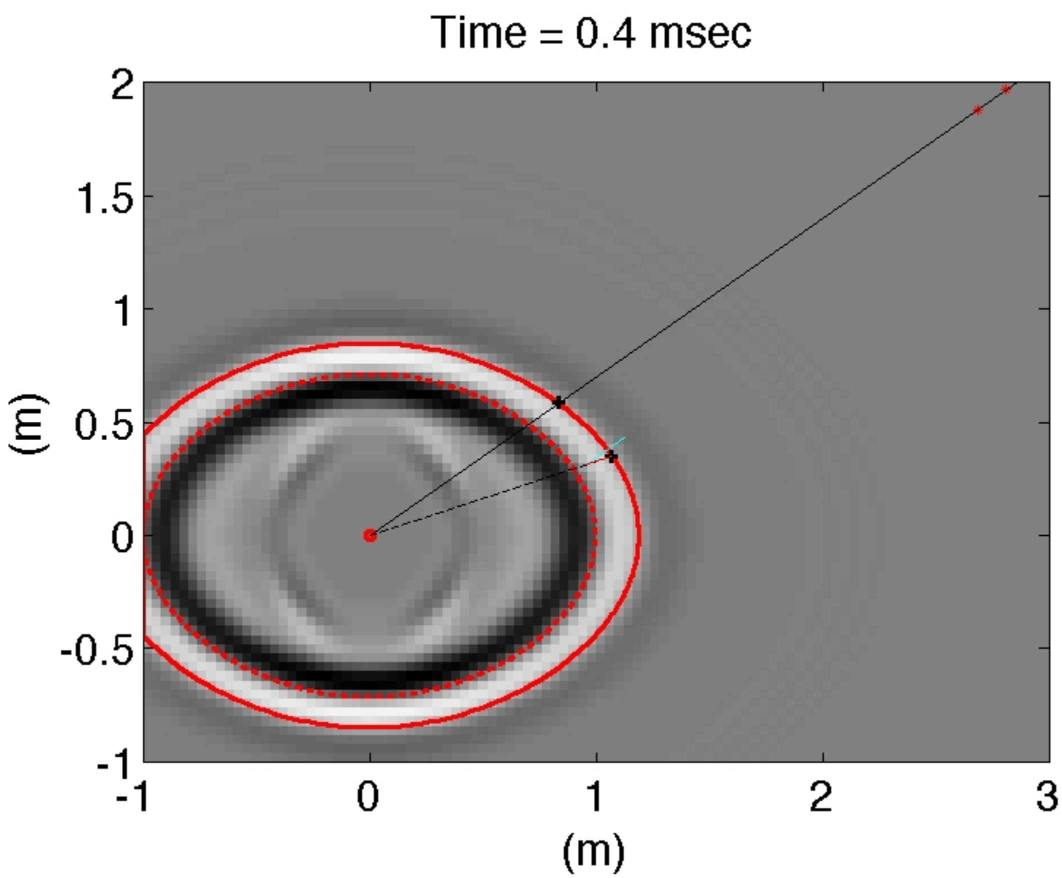
- Group direction points to source
- Phase direction is normal to wavefront

Phase and Group



- Wavefront expands without changing shape
- Group direction points to source
- Phase direction is normal to wavefront
- Marked points have 55 degree group and phase angles respectively

Phase and Group



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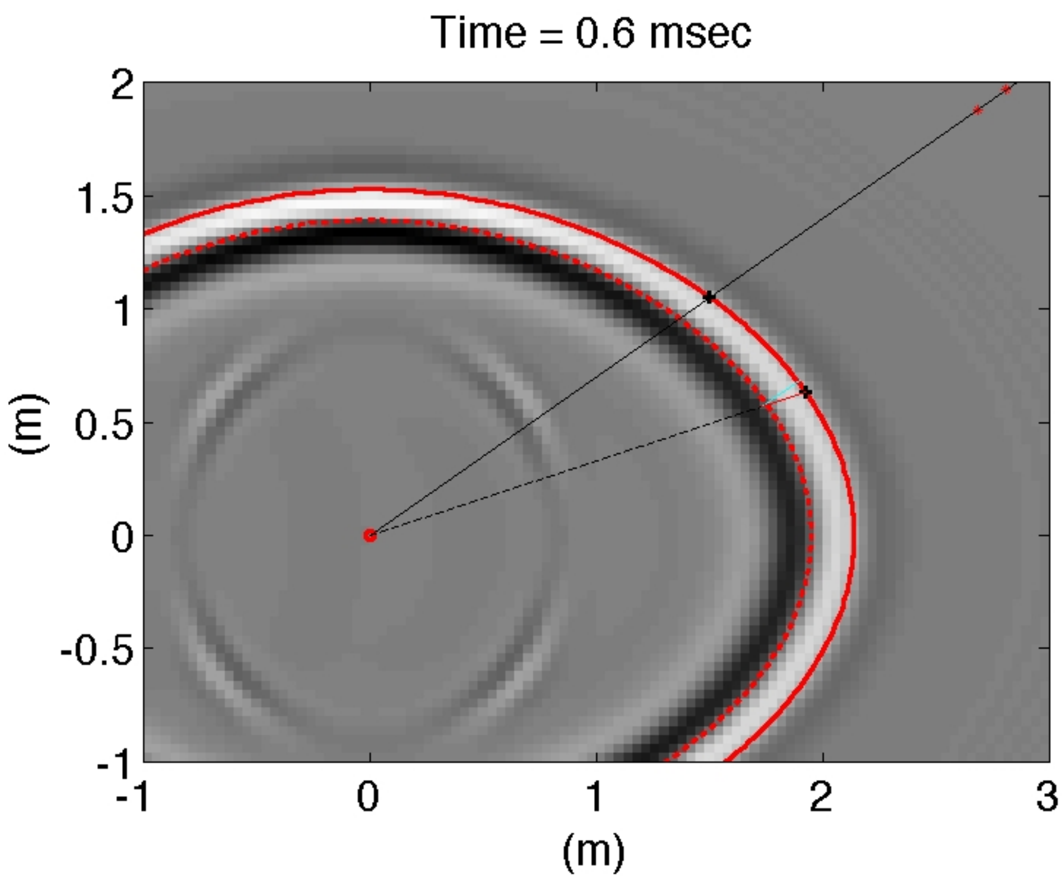

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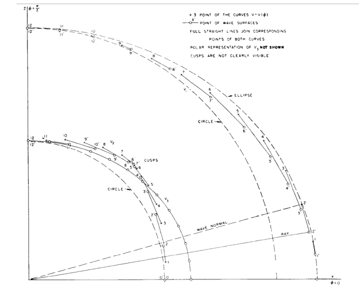
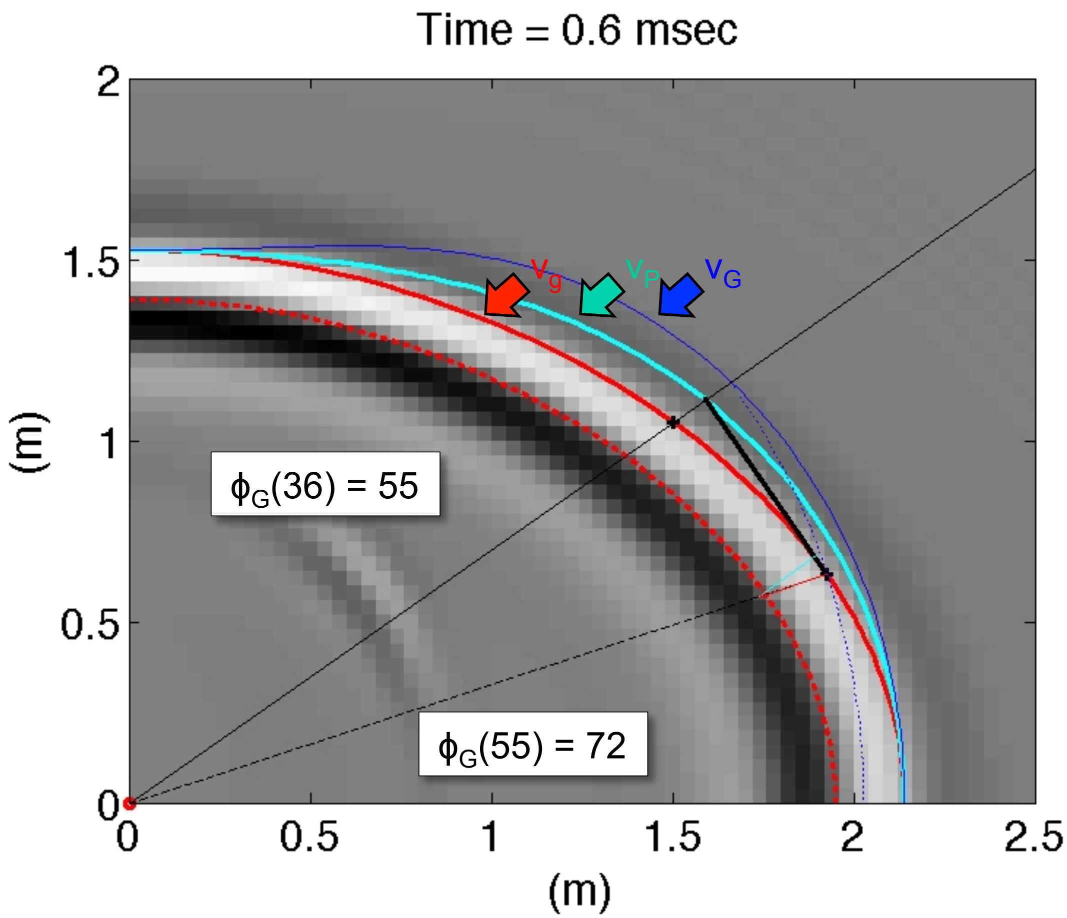


Postma 1955



- v_g is **Group velocity(group angle)**
- v_P is **Phase velocity(phase angle)**
- v_G is **Group velocity(phase angle)**

- v_g matches the wavefront

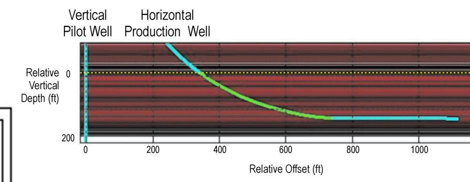
- v_P , v_G and ϕ_G can be computed algebraically from phase angle

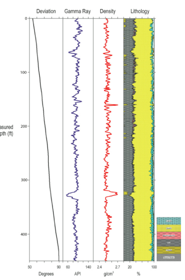
- v_g must be interpolated as
  $v_G(\phi_G(\text{phase angle}))$

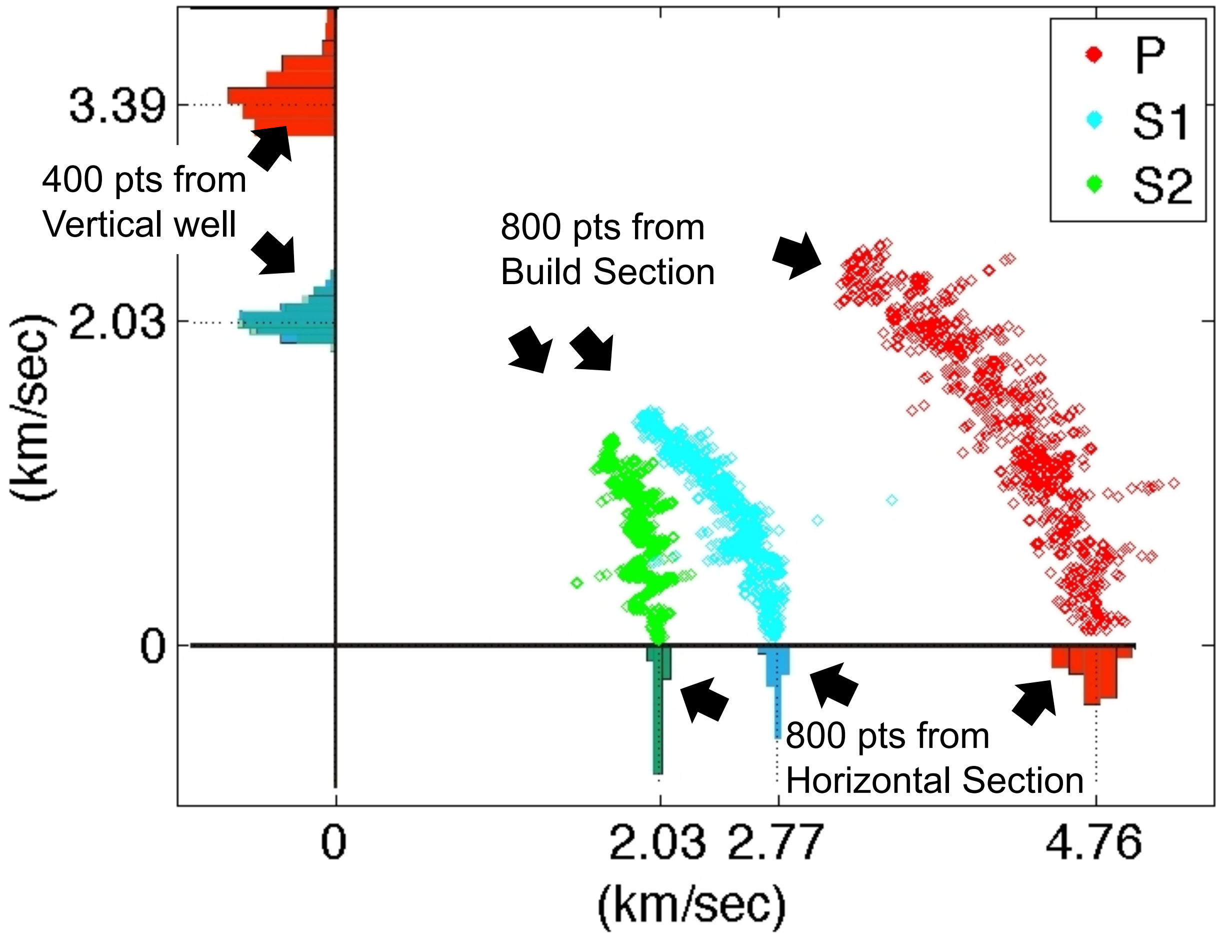
- For qP and SH modes in TI media, and all ψ,

$$v_G(\psi) \geq v_P(\psi) \geq v_g(\psi)$$

Sonic Log Data from a Gas Shale







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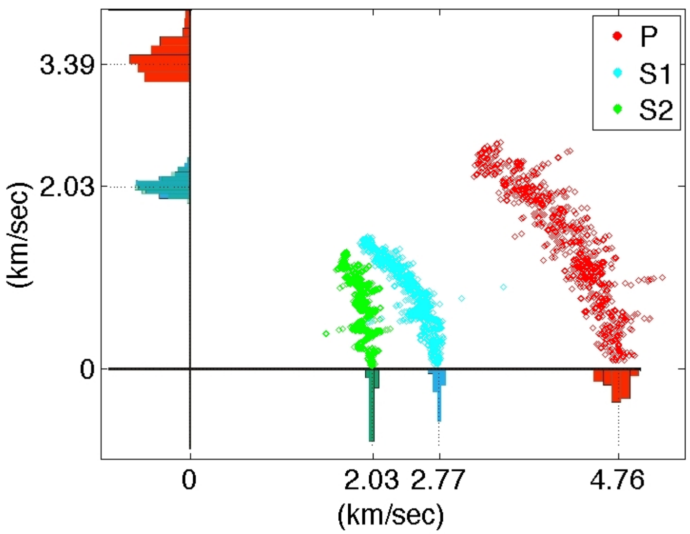
- TI anisotropy, lateral and vertical homogeneity are evident from axial data

Four Moduli Directly from Axial Data

- C13 remains to be found by a 1-parameter search
- We need to know how C13 relates to off-axis log speeds (i.e. a Correspondence Rule)



	Vertical Well		Horizontal Well			Units
Velocity	V_{33}	V_{31}	V_{11}	V_{13}	V_{12}	
Mean	3.39	2.03	4.76	2.03	2.77	km/sec
RMS variation	0.13	0.07	0.11	0.03	0.05	km/sec

Modulus	C_{33}	C_{55}	C_{11}	C_{66}	
	29.0	10.4	57.0	19.3	GPa

Thomsen	α_0	β_0	ϵ	γ
	3.39	2.03	0.48	0.43

density	ρ	kg/m^3
	2520	

Correspondence Rules: Hornby vs. Sinha

SEG Expanded Abstracts 2003
Do We Measure Phase Or Group Velocity With Dipole Sonic Tools?
B. Hornby, X. WANG And K. Dodds

Comparisons of the computed velocities with the theoretical wave surfaces clearly shows the best fit with the group velocity surfaces. And so ***we conclude that we are measuring the group velocity*** *for all wave modes excited by the dipole sonic tool.*

GEOPHYSICS, 71(6) 2006 191–202
Elastic-wave propagation in deviated wells in anisotropic formations
B. Sinha, E. Şimşek, and Q. Liu

Processing of synthetic waveform*s in deviated wellbores using a conventional STC algorithm or a modified matrix pencil algorithm* ***yields phase slownesses*** *of the compressional and shear waves propagating in the nonprincipal directions of anisotropic formations.*

The full-wave processing of dipole sonic logs using slowness time coherence has been demonstrated to yield phase rather than group velocities of compressional Vp and shear Vs waves (Sinha et al., 2006). This finding is imperative to the problem discussed in this paper because the angle dependence of phase and group velocities in anisotropic media can be quite different (Thomsen, 1986; Vernik and Liu, 1997).

- Vernik 2008, Geophysics

Correspondence Rules: Hornby and Sinha

(GG) *Logs measure **group slowness** for propagation with the **group angle** equal to the borehole inclination angle* (Hornby et al. 2003)

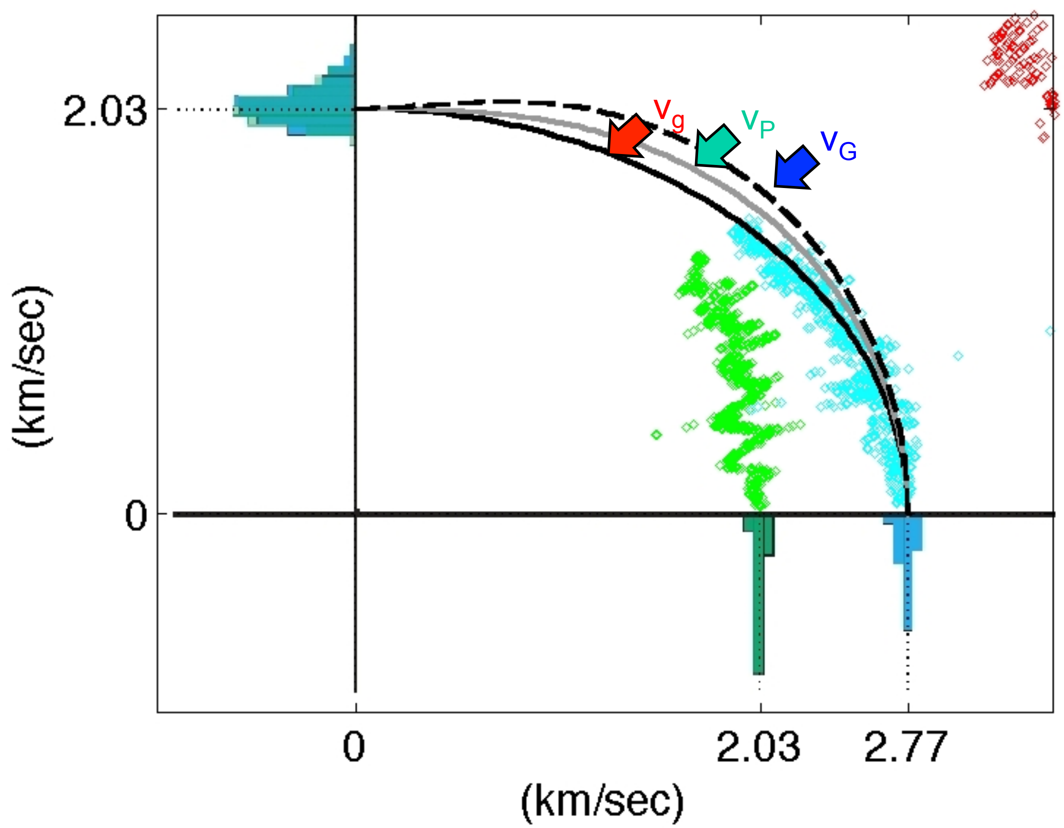
(PP) *Logs measure **phase slowness** for propagation with the **phase angle** equal to the borehole inclination angle* (Sinha et al. 2006)

When anisotropy is strongly present, these rules are incompatible. For the case at hand, (GG) is uniquely consistent with the data and matching synthetics. Sinha et al. reached their conclusion by confusing Hornby's rule with a different one:

(GP) *Logs measure **group slowness** for propagation with the **phase angle** equal to the borehole inclination angle* (Sinha et al. 2006)

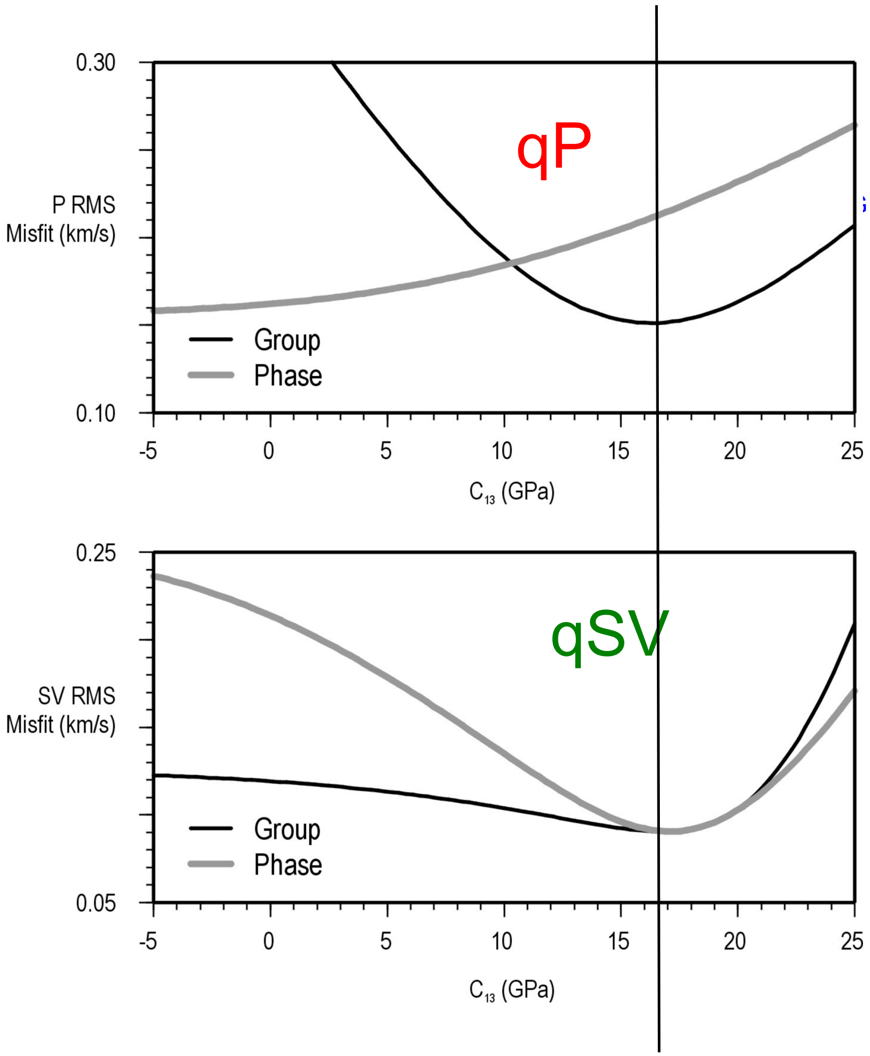
That is, Sinha et al. compared v_P with v_G rather than with v_g.

SH Comparison



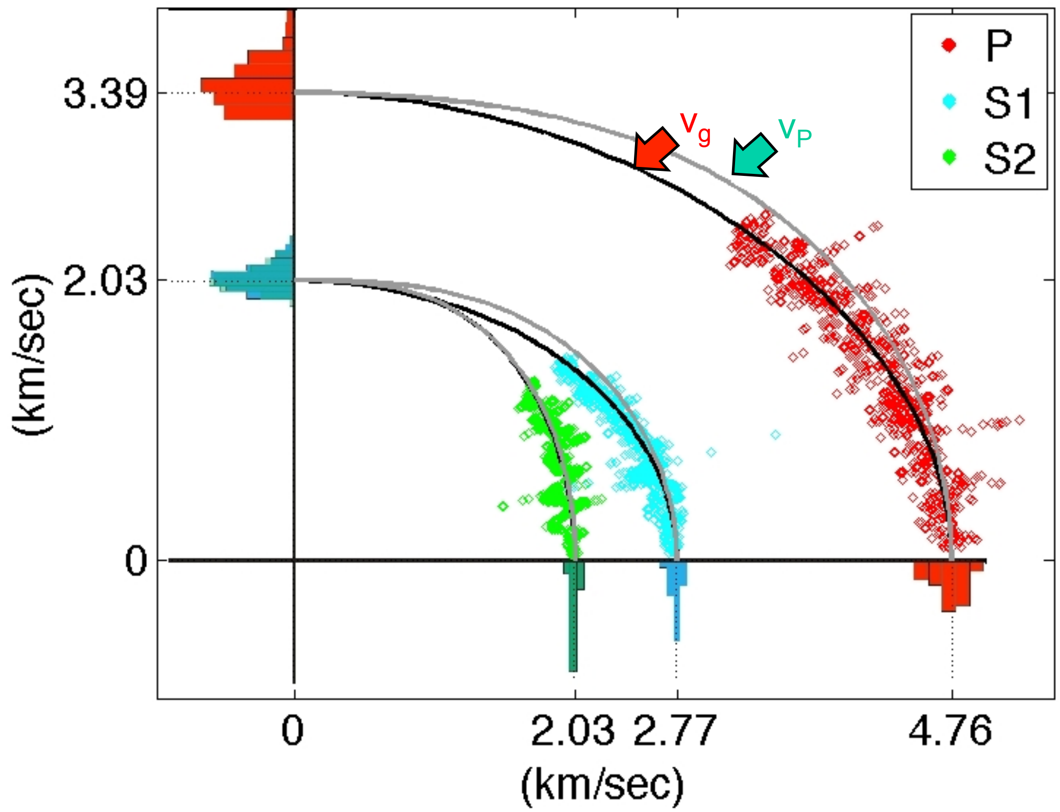
- There are no adjustable parameters. Curves are determined by shear slownesses from horizontal well.
- (GG) fits. (PP) and (GP) do not.
- (GG) RMS misfit is .029 km/sec
- (PP) RMS misfit is .082 km/sec

C13



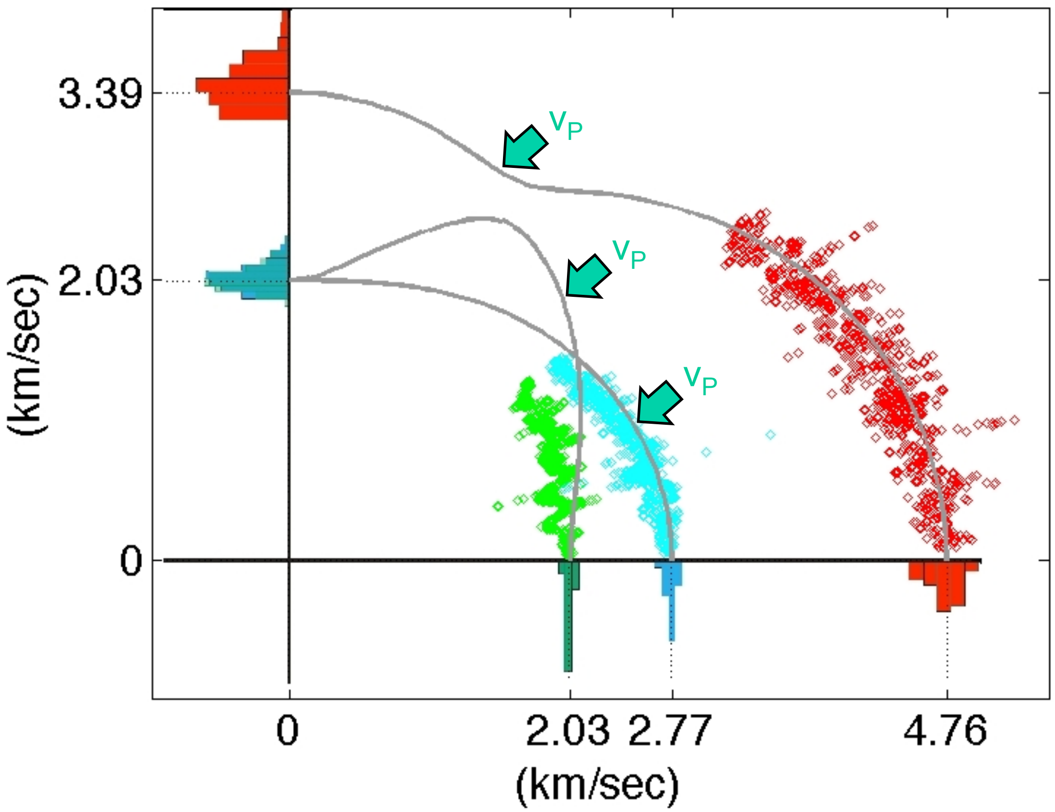
- Figures at left show RMS misfit as a function of C13 for (GG) in black, (PP) in gray.
- (GG) fits both modes at C13 = 16.4 GPa
- (PP) does not give a consistent answer
- qSV best fit agrees with (GG) because, in this case, qSV phase and group surfaces are nearly coincident.
- (PP) best fit for qP is physically unreasonable, -5 GPa.

(GG) Best Fit



- v_g in black, v_P in gray, for each mode, using the (GG) best-fit value, C13 = 16.4 GPa
- (GG) fits all modes
- (PP) only fits qSV, (where phase and group surfaces happen to coincide).

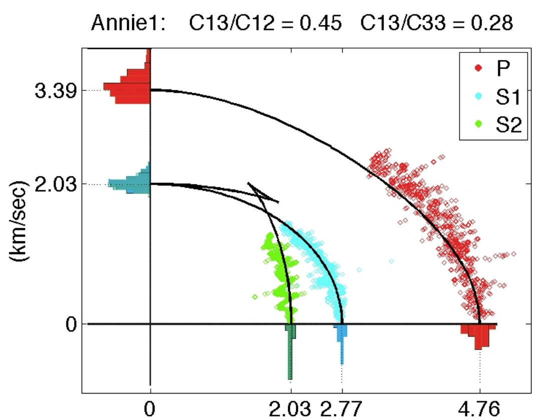
(PP) Fit to qP Data



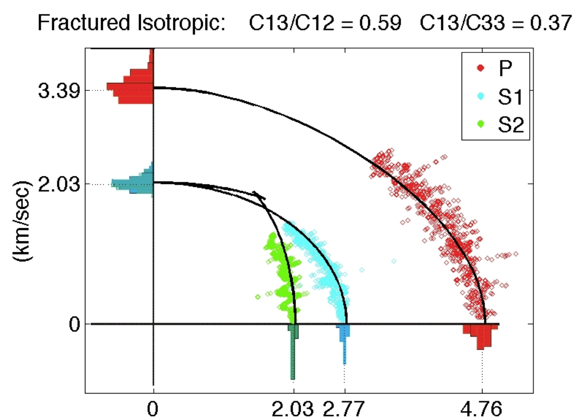
- v_P in gray for each mode, using the value C13 = -5 Gpa, which fits the qP data with the phase surface.

- qSV is egregiously misfit, with coincident shear speeds predicted at 55 degrees.

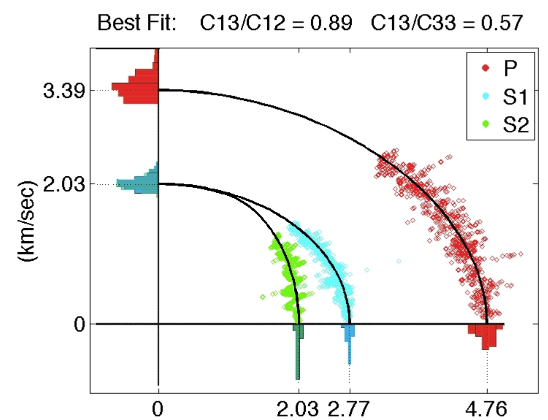
Best-Fit and 4-Parameter Approximations



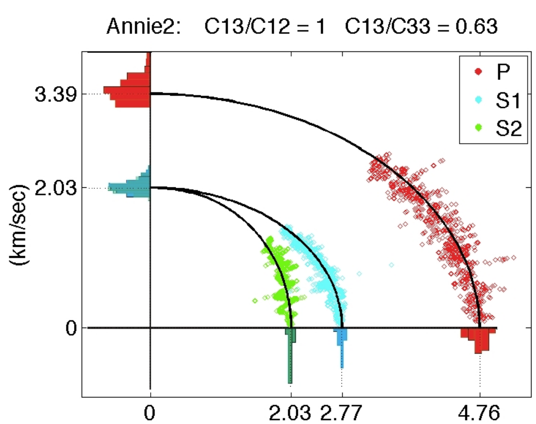
δ = 0;
C13 = C33 – 2 C55



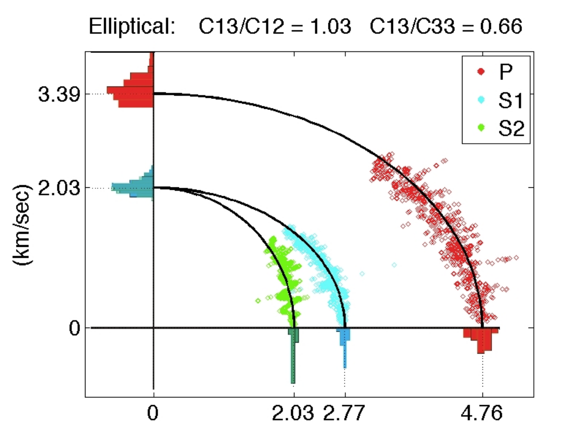
δ = .1;
C13 = -C66 + sqrt(C66² + C12 C33)



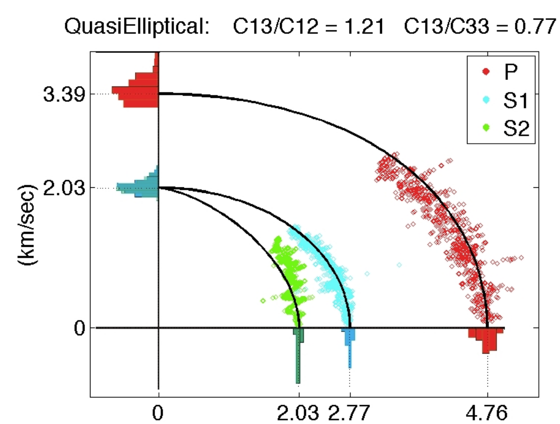
δ = .35;
C13 = 16.4 GPa



δ = .45;
C13 = C11 – 2 C66



δ = ε=.48;
C13 = sqrt(C11 – C55) (C33 – C55))



δ = .54;
C13 = (C11 + C33)/2 – 2 C55

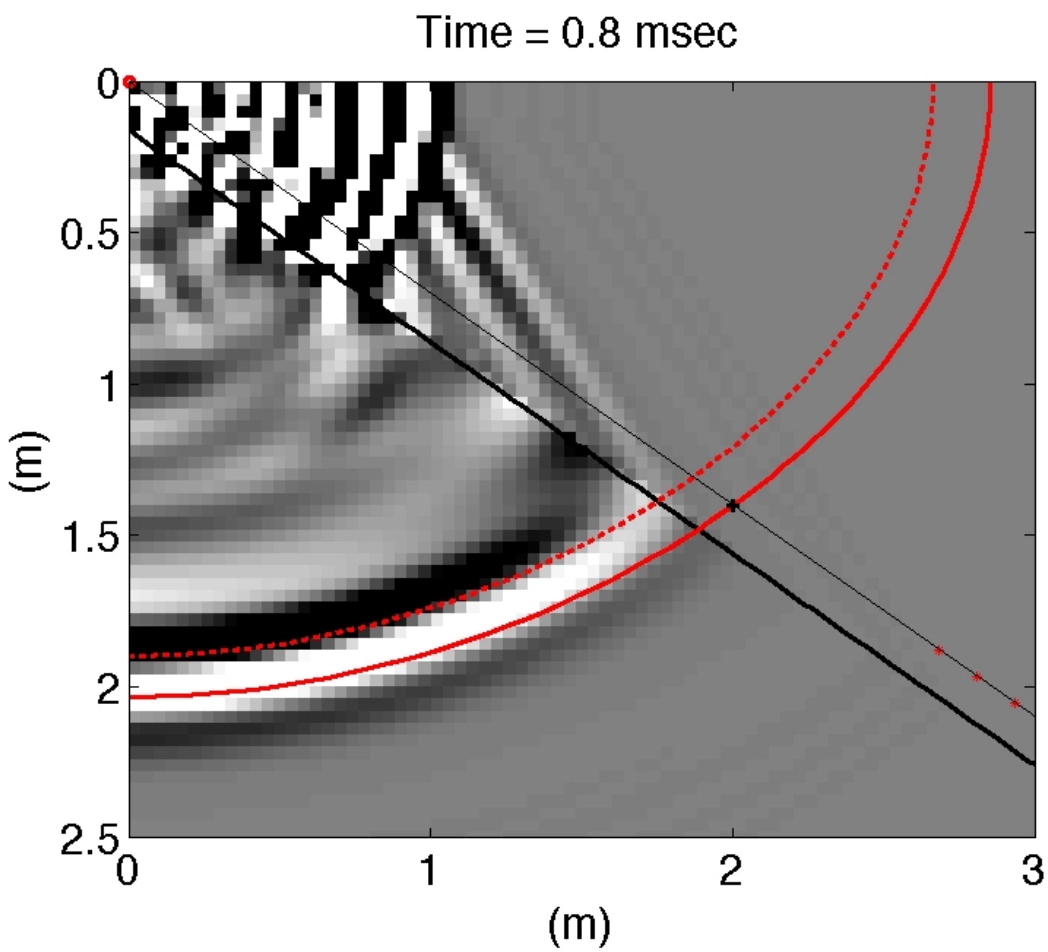
Miller, Horne, Walsh, 1IWRP August 2011

Best-fit Parameters

Modulus	C_{11}	C_{13}	C_{33}	C_{55}	C_{66}
	57.0 $\pm$2.5	16.4 $\pm$1.5	29.0 $\pm$2.0	10.4 $\pm$0.3	19.3 $\pm$0.7

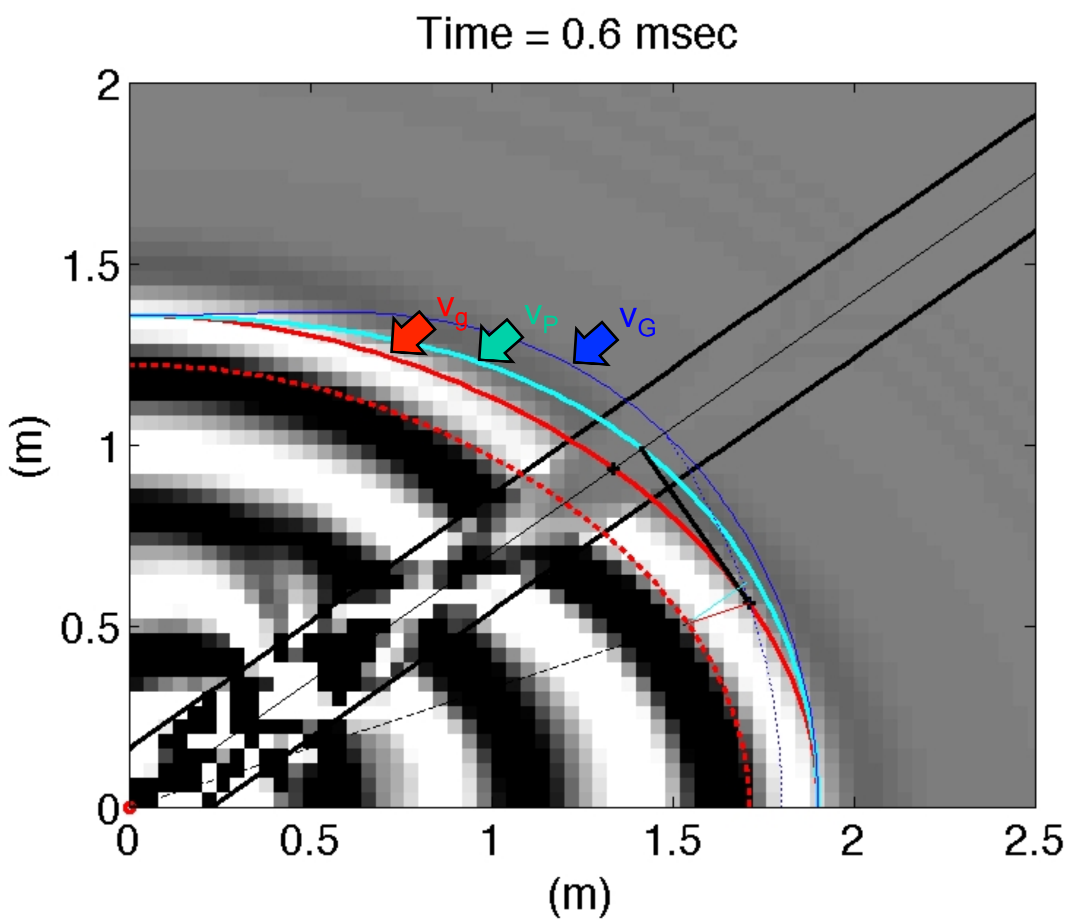
Thomsen	α_0	β_0	ϵ	δ	γ
	3.39 $\pm$0.11	2.03 $\pm$0.05	0.48 $\pm$0.05	0.35 $\pm$.025	0.43 $\pm$.015

3DFD



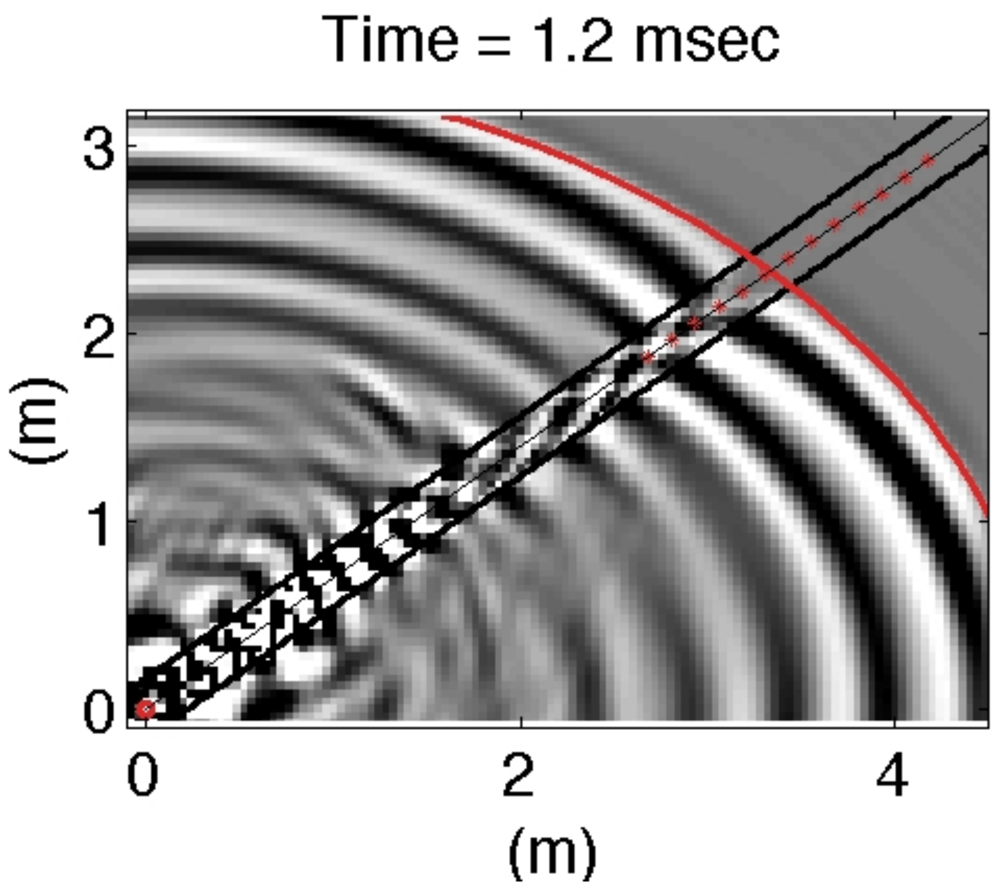
- Monopole source in fluid above an inclined half-space
- Propagation in the solid matches the anisotropic wavefront surface, shedding a headwave.

3DFD



- Monopole source in fluid-filled borehole
- Wavefront in solid couples to reverberant “leaky P’ signal in borehole.
- Signal in borehole slightly lags the wavefront in the solid.

3DFD



- Monopole source in fluid-filled borehole
- Wavefront in solid couples to reverberant “leaky P’ signal in borehole.
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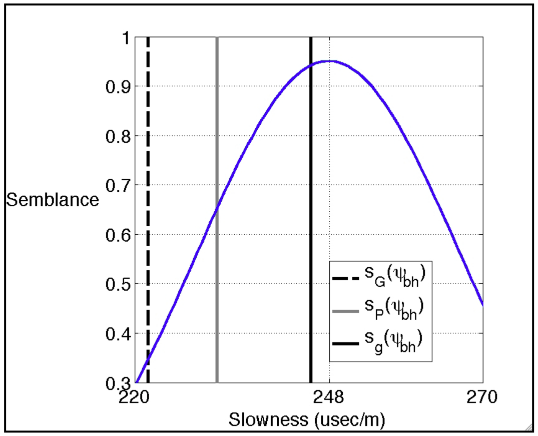
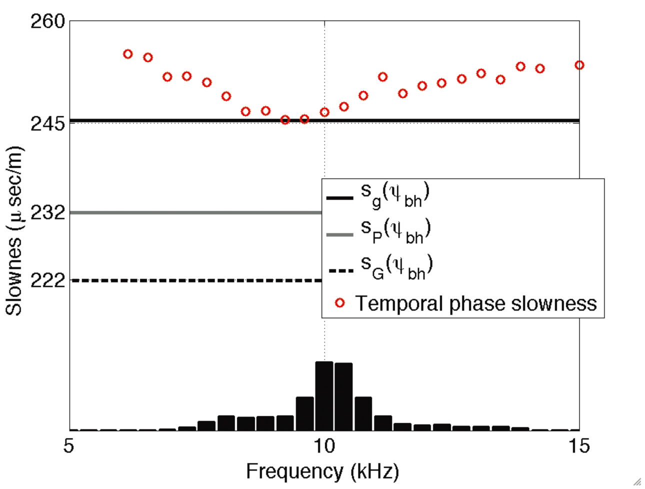
3DFD Processing

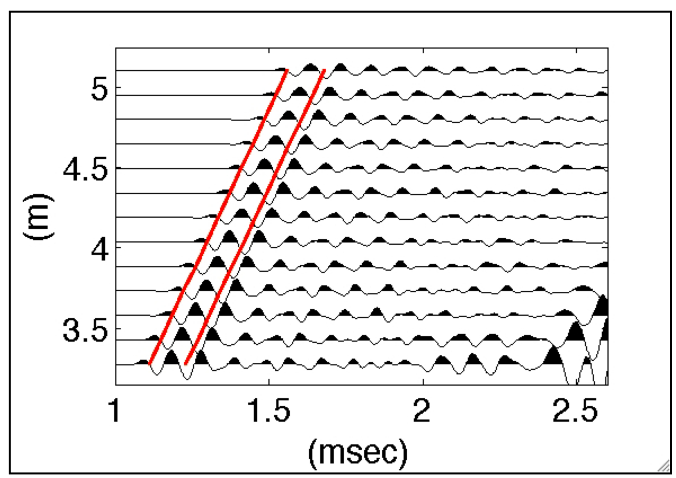




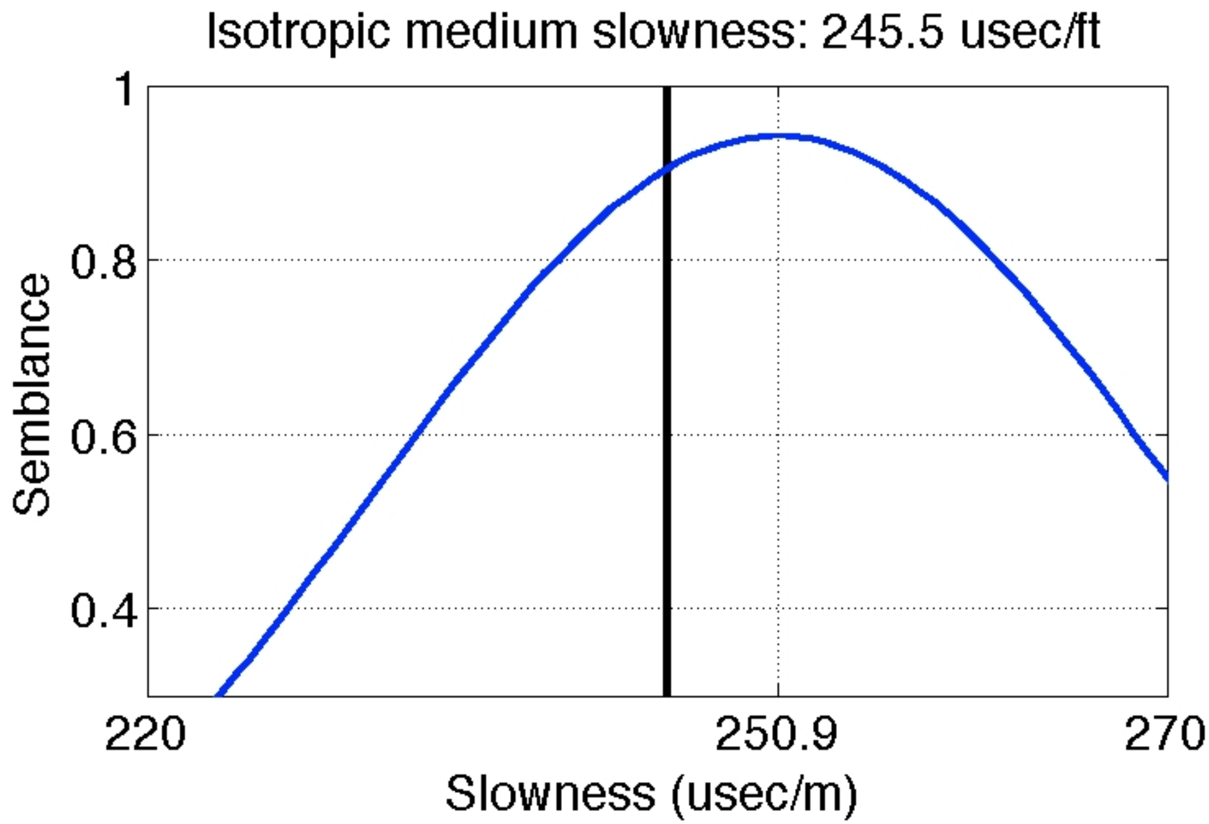
- Waveforms and processing confirm what is evident in the snapshots

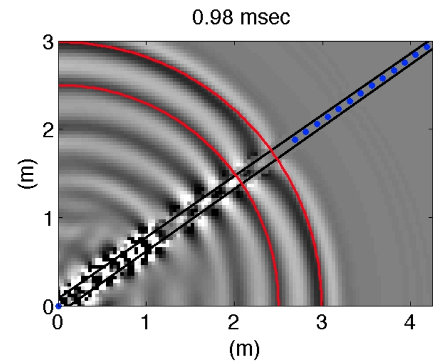
- Semblance peaks are about 1% slower than $1/v_g$; 7% slower than $1/v_P$; 12% slower than $1/v_G$.

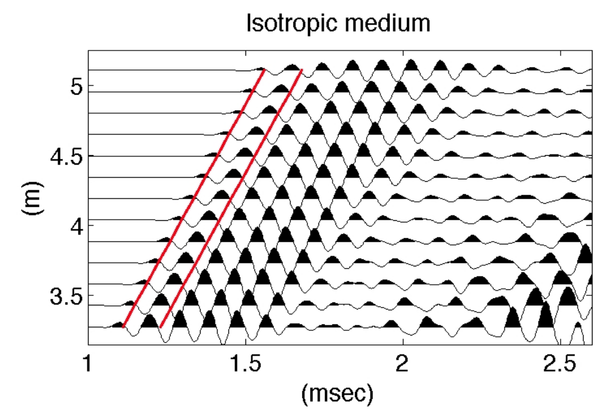
- Temporal dispersion analysis using the Prony method yields a similar result. Temporal phase slowness at all frequencies is slower than $1/v_g(\psi_{bh})$



Isotropic Example

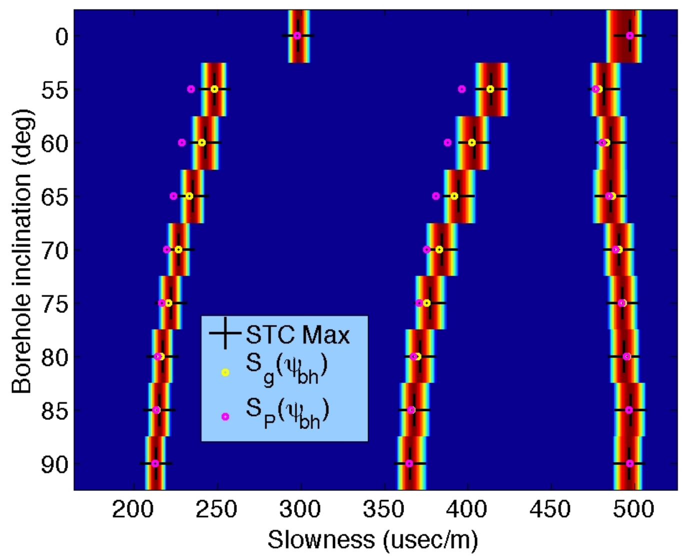






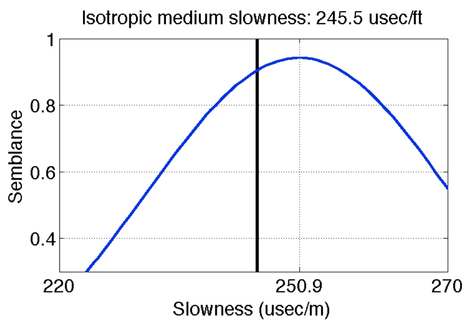
- Semblance peak is 2% slower than medium slowness

Bias Correction



- The small bias between logged slowness and formation slowness is a feature of sonic logs that has always been present.

- Processing all modes and angles in our synthetics, we found that a uniform 2% increase in elastic moduli gave an excellent match between semblance peaks and group slowness.



Modulus	C_{11}	C_{13}	C_{33}	C_{55}	C_{66}
	58.1 $\pm$2.5	16.6 $\pm$1.5	29.6 $\pm$2.0	10.6 $\pm$0.3	19.7 $\pm$0.7

Thomsen	α_0	β_0	ϵ	δ	γ
	3.43 $\pm$0.11	2.05 $\pm$0.05	0.48 $\pm$0.05	0.35 $\pm$.025	0.43 $\pm$.015

Concluding Remarks

1) Log data from this field example are remarkably consistent with the rule that sonic logs measure **group slowness** for propagation with the **group angle equal to the borehole inclination angle**. The data are inconsistent with an interpretation that they measure phase slownesses for propagation with phase angle equal to borehole inclination angle.

2) Processed 3DFD synthetics simulating best-fit model confirm the interpretation.

3) The best-fit model is close to satisfying the second Annie condition C13 = C12, as well as the elliptical condition, $\varepsilon = \delta$.

4) Data from deviated well alone would have been sufficient (but less convincing).

5) See the extended abstract for more details. I'll put a copy at www.mit.edu/~demiller

Thanks to:

- Coauthors
- Yang Zhang at MIT, Earth Resources Lab for help installing the 3DFD cone on my Mac mini
- Phil Christie, David Johnson, Chris Chapman for helpful comments
- The operating company for permission to show the data