Observations of Intrinsic Anisotropy in Varied Geologic Settings*

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Abstract

Acoustic anisotropy in unconsolidated sediments and sedimentary rocks is a function of both the intrinsic character of the material and variability in the externally applied stress field. This paper reports measured intrinsic, acoustic anisotropy in unconsolidated sands and mud rocks from fold-thrust belts, from sub-salt settings, and for sands in typical extensional basin settings. In the latter, the vertical effective stress has been the principal stress throughout the sand's burial history. This is in contrast to thrust belt settings in which the principal stress is non-vertical for some portion of the burial history, or to sub-salt settings in which horizontal stress gradients arise due to rapid changes in salt thickness. Both polar and azimuthal acoustic properties were measured. Laboratory measurements were made under isostatic stress conditions at the estimated in situ stress. Analysis of grain contact length and orientation, and of grain fracture and intergranular pore bodies was performed on thin sections from fast and slow orientations. The influence of layer parallel compaction in the thrust belt samples (and to a somewhat lesser extent in the sub-salt samples) is evidenced by the rotation of grain contacts out of the bedding plane and into a direction perpendicular to the fast azimuthal velocity. Intrinsic azimuthal anisotropy in the thrust belt sands averaged 15% in both crestal and flank structural positions. Anisotropies as high as 30% were observed locally, in proximity to deformation bands and minor faults. In this setting, polar anisotropies tend to be substantially lower than the azimuthal values, averaging about half the azimuthal anisotropy. This observation suggests that a TI medium assumption would be inappropriate in fold and thrust belt settings. In contrast, interbedded mud rocks showed azimuthal anisotropies on the order of 7-8%. In sub-salt settings the degree of azimuthal anisotropy in sands ranged from 5-10% at in situ stress. In extensional basin settings, measured azimuthal anisotropy ranged from 0-3%. In these samples the polar anisotropy is larger than the azimuthal value, and varies depending upon the compaction state of the sands. In all cases this level of anisotropy measured in the core plugs could be directly tied to textural changes observed in thin section.

Observations of Intrinsic Anisotropy in Varied Geologic Settings

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Acknowledgements: D.K. Love, M.M. Arasteh, J. Rask, R. Vines, B. Couzens

Note by Presenter: You can find all the Templates for Presentations on the Graphics Web site. **Visit our web page:** sww.siep.shell.com/graphics (under "Templates")

Importance of Understanding the origins of Intrinsic Acoustic Anisotropy

- ***Assess the relative importance of vertical effective stress and elevated horizontal effective stress to sand/sandstone compaction in complex geologic settings (e.g. thrust belts, proximal to salt/shale diapirs)***

- ***Develop porosity/velocity prediction techniques for sands in these settings to aid in quantitative seismic interpretation***

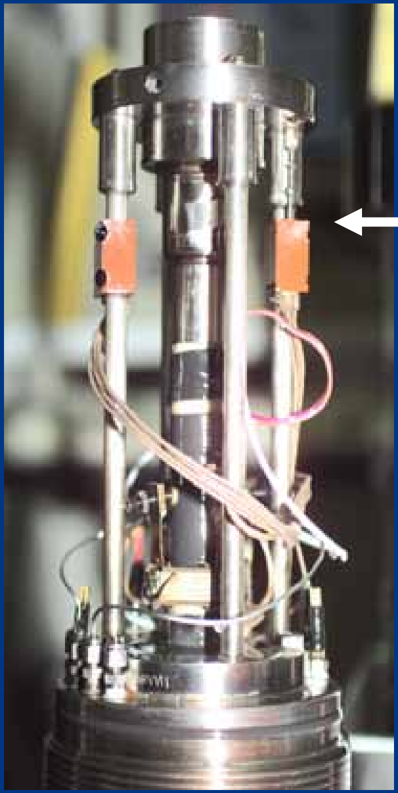
Origins of Intrinsic Acoustic Anisotropy: Important Factors to Consider

- *Textural and mineralogic characteristics of the sand*
  Are there differences in anisotropy development in ductile-grain-rich versus brittle-grain-rich sands?

- *Timing of the onset of elevated horizontal stress*
  What is the compaction state of sand/sandstone at the onset of elevated horizontal stress?
  What authigenic cements are present and what is their distribution?

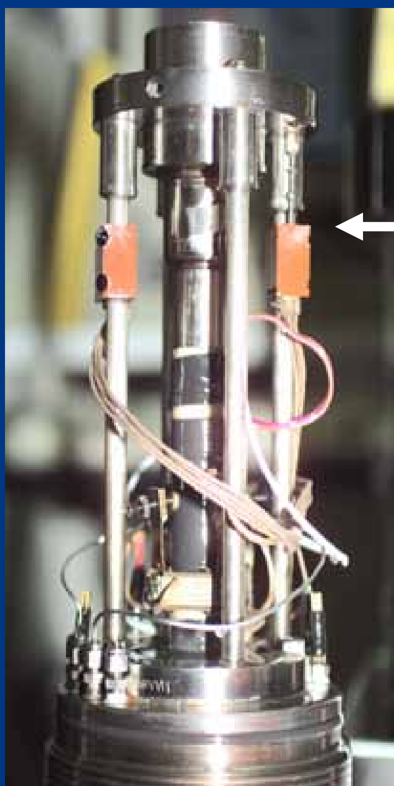
- *Influence of structural position*
  Are there differences between crest and flank in a single structure?
  Are there differences with position along strike?

Laboratory Data Linked to Shell-Proprietary Image Analysis



State-of-the-art measurement system, capable of triaxial, isostatic, and uniaxial strain measurements with simultaneous measurement of petrophysical properties (e.g. acoustics, electrical, permeability, etc.)

Laboratory Data Linked to Shell-Proprietary Image Analysis



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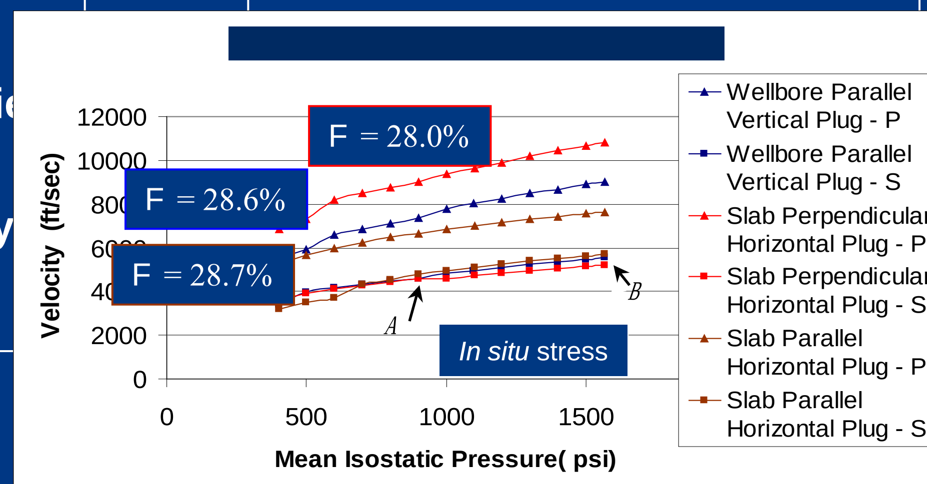
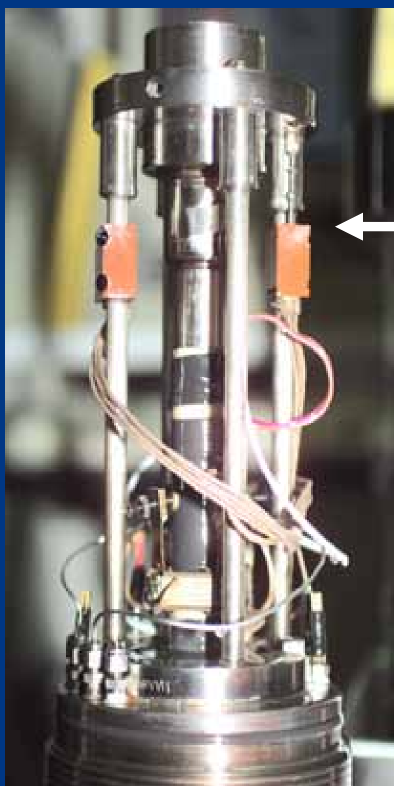
Phase 1: 1D

- **Three mutually perpendicular plugs with axial velocity measurements**
- **Isostatic stress state; measurements made at *in situ* stress inferred**



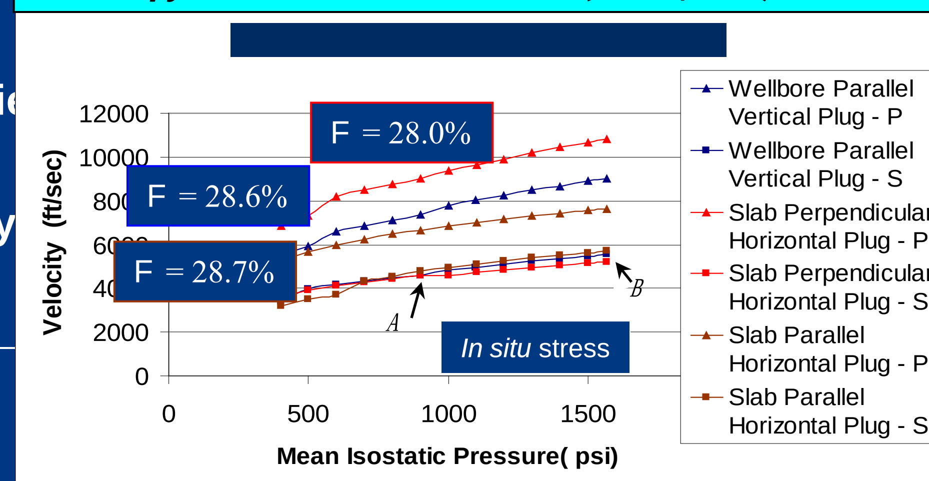
Laboratory Data Linked to Shell-Proprietary Image Analysis



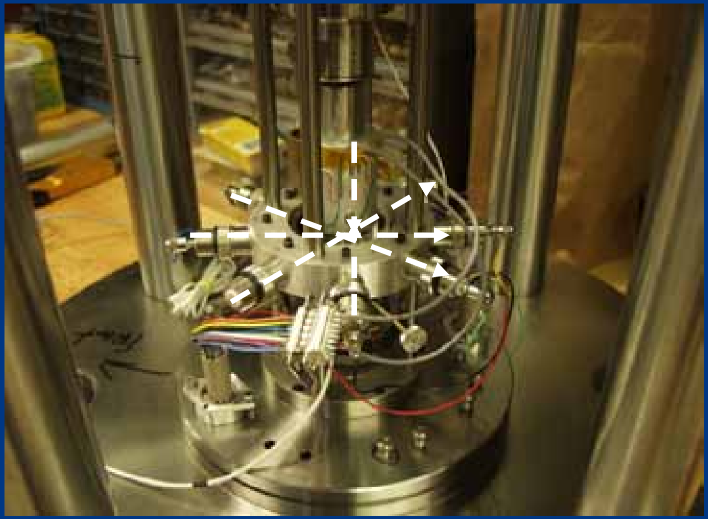
State-of-the-art measurement system, capable of triaxial, isostatic, and uniaxial strain measurements with simultaneous measurement of petrophysical properti (e.g. acoustics, electrical, permeability etc.)

Phase 1: 1D
- **Three mutually perpendicular plugs with axial velocity measurements**
- **Isostatic stress state; measurements**

Anisotropy based on axial velocities = (10867/7650) - 1 = 0.41

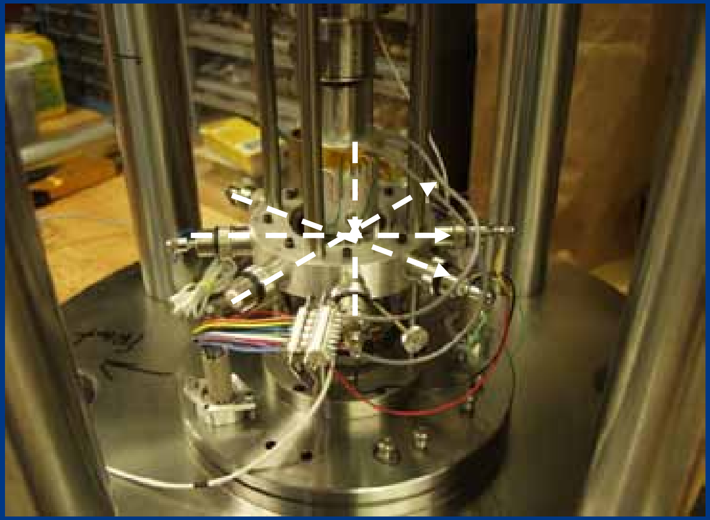


Laboratory Data Linked to Shell-Proprietary Image Analysis

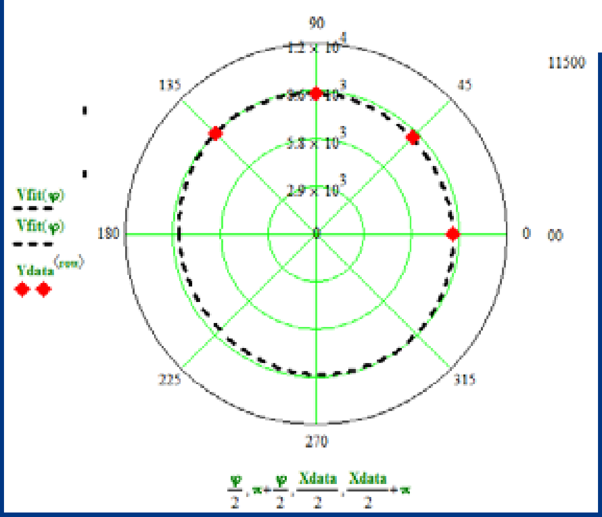


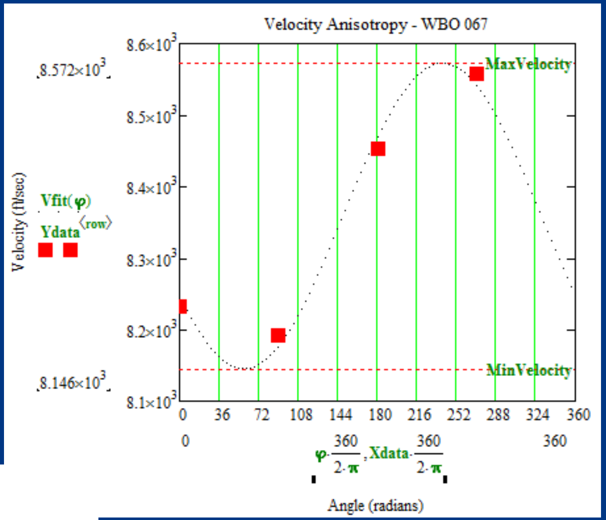
Newly-developed technique for azimuthal anisotropy measurement. The ring of transducers can be moved along the length of the plug to make multiple measurements

Laboratory Data Linked to Shell-Proprietary Image Analysis



Newly-developed technique for azimuthal anisotropy measurement. The ring of transducers can be moved along the length of the plug to make multiple measurements





For the figure at left:

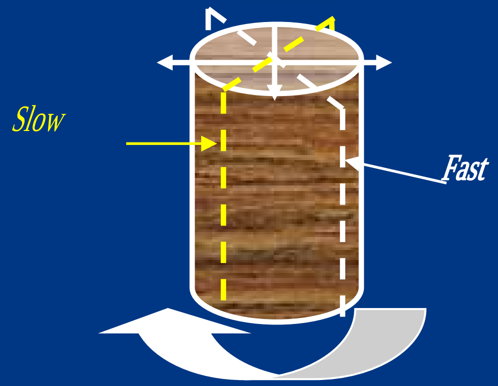
- Outer circle is azimuth
- Green grid lines are velocity contours
- Red points are measured data
- Dashed line is the ellipse that best fits the velocity data

Image-based Rock Properties Modeling

- Make directional measurements of velocity, permeability on a vertical plug (perpendicular to bedding)
  - Use isostatic stress condition

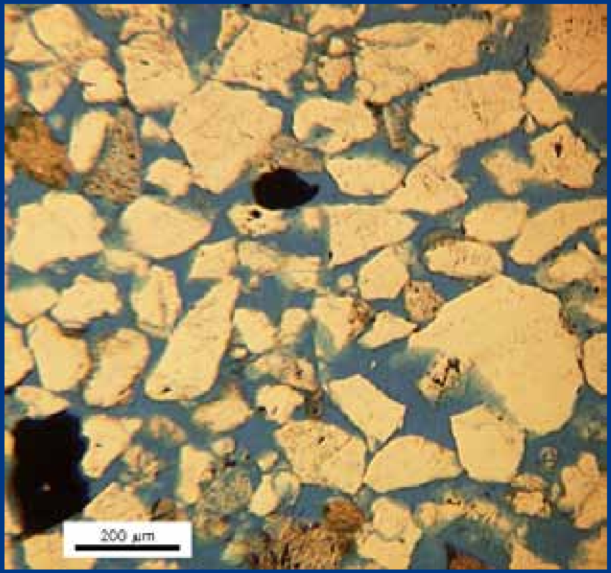
Vertical Plug

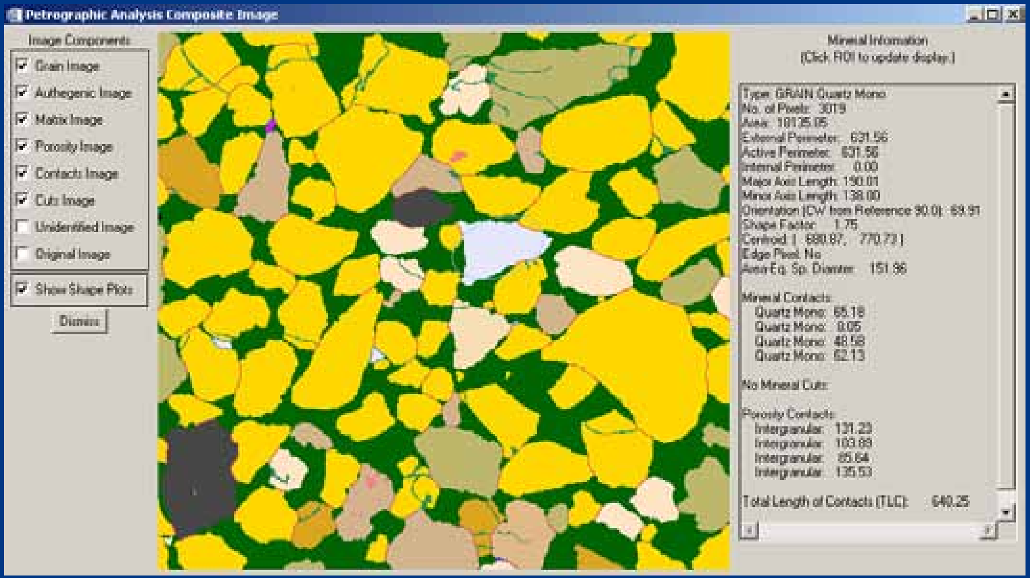
0º

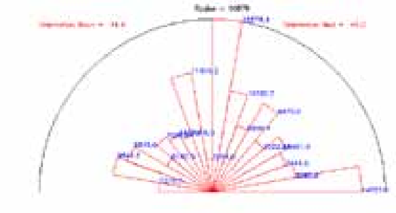


- Identical stress state regardless of plug orientation eliminates stress-induced velocity changes
  - Measured differences in velocity are inferred to result from intrinsic anisotropy
  - Image analysis will be performed on longitudinal and end trim sections from each plug

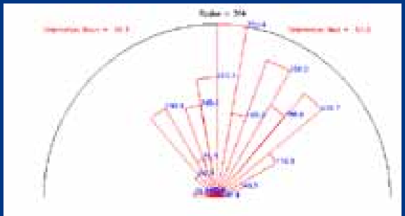
Laboratory Data Linked to Shell-Proprietary Image Analysis



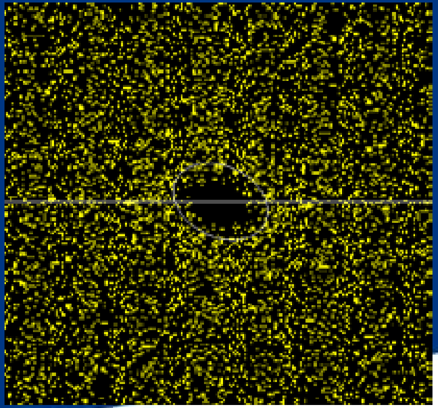




Normalized grain contact orientation



Normalized fracture porosity orientation



Summary of Anisotropy Measurements

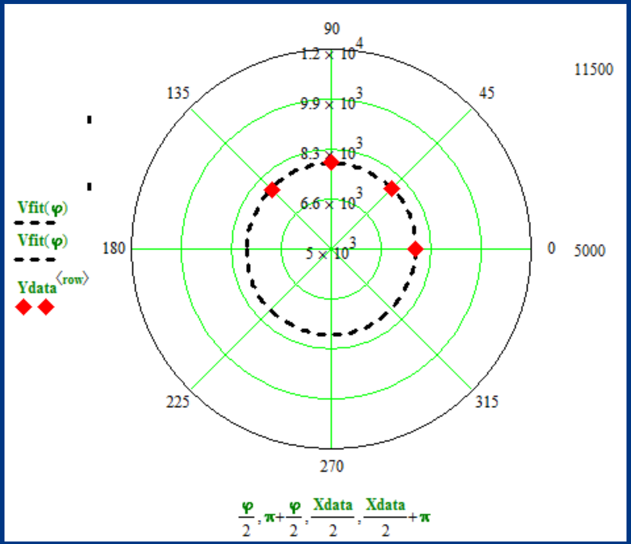
Sample ID	Vp Hmin**	Vp Hmax	Vp V	Vp Vlog	AZ anisotropy	Polar Anisotropy(ave)
T1*Crest	8500	9880	9412	8750	16.00%	2.40%
T2 Crest	9031	10774	11214	10521	17.00%	13.00%
T3 Crest	8567	9720	9772	9367	12.00%	6.80%
T4 Flank	8600	11047	9412	9007	28.00%	4.20%
T5 Flank	9860	10586	10047	10084	7.00%	1.70%
T6 Flank	8520	9850	10760	10181	15.00%	17.10%
Average					***15.83%***	***7.53%***
T7 MR	11902	12764			7.24%	
T8 MR	9340	10406	10221		11.41%	3.50%
SS1***	7028	7494	7228		6.60%	0.50%
SS2	9040	9518	9385		5.30%	1.10%
SS3	6841	7972	7931		16.50%	7.00%
SS4	7311	8293	7780		13.40%	0.20%
SS5	9373	9899	9700		5.60%	0.60%
Average					***9.48%***	***1.88%***
Null1	7743	7804	7200		0.80%	7.40%
Null2	7340	7601	7885		1.04%	5.60%

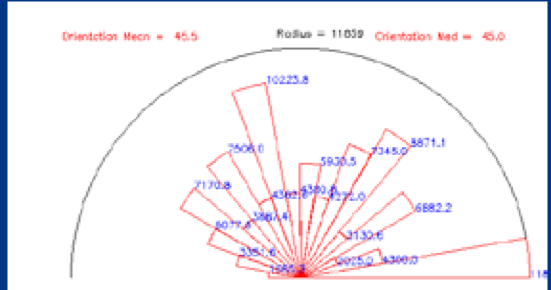
***   T = Thrust belt Sample***

*** **   All velocities are in ft/sec***

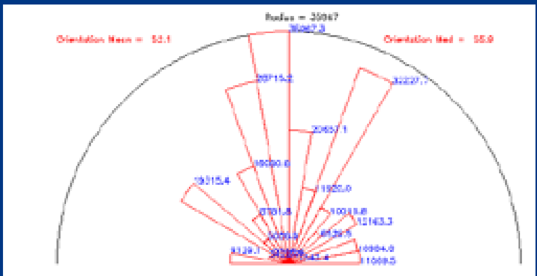
****** SS = Sub-salt Sample***

Azimuthal Anisotropy Measured in Normally Compacted Settings





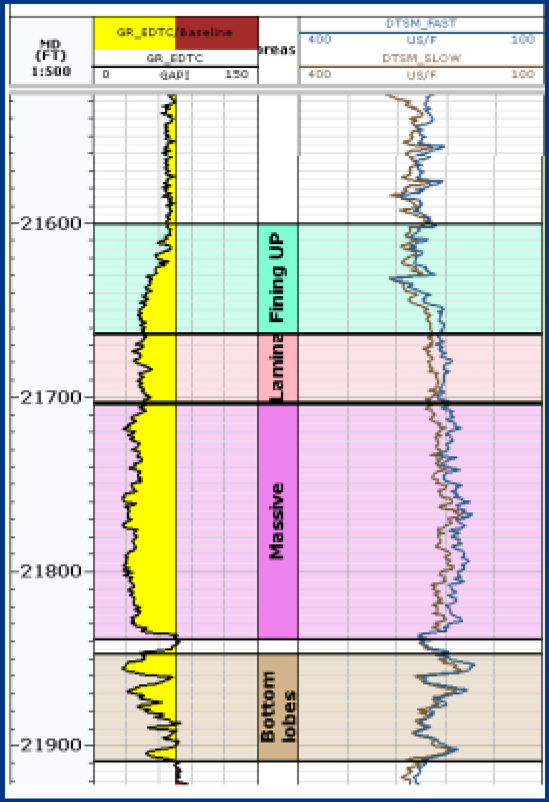
Normalized contact length in end trim thin section



Normalized grain orientation in end trim thin section

- In normally compacted settings, measured azimuthal acoustic anisotropy is on the order of one percent.
- This is consistent with the nearly isotropic distribution of normalized grain contact lengths.
- Apparent preferred orientation of grain long axis orientation is not reflected in the acoustic properties .

Azimuthal Anisotropy Measured Sub-Salt

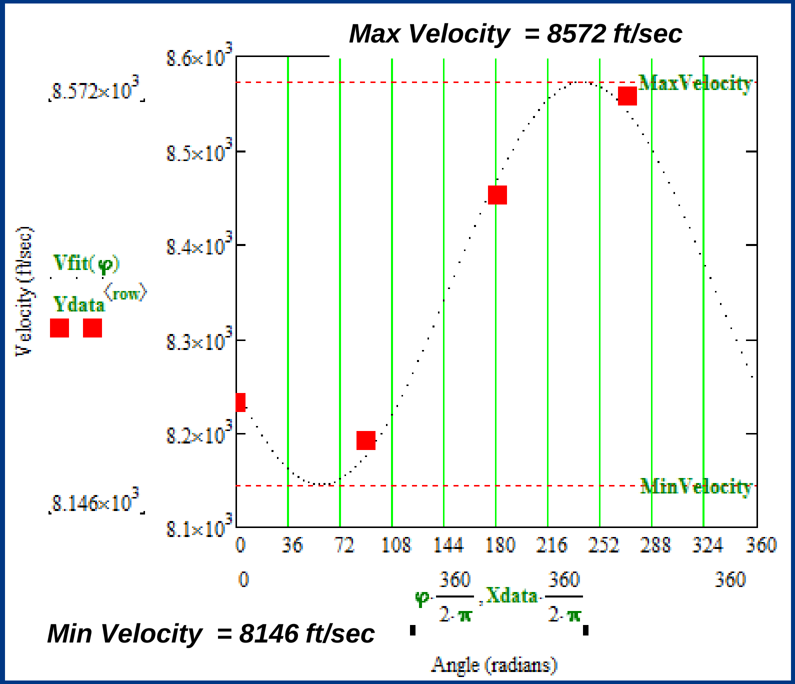


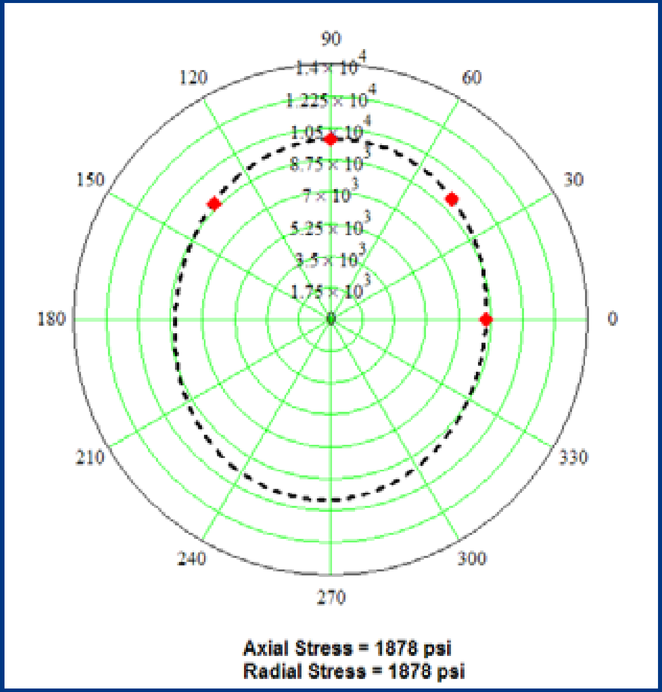
In this near vertical well we see shear anisotropy in the sands.

The polarization of the faster wave is inferred to be aligned with the regional stress field.

Shear splitting suggests that the "stress-induced" anisotropy in the sands is on the order of 7%

Azimuthal Anisotropy Measured Sub-salt



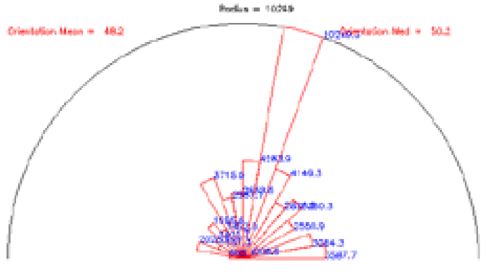


Anisotropy based on azimuthal velocities = (8572/8146) - 1 = 0.052

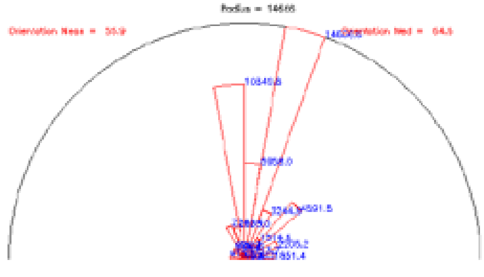
Note that this value, measured under isotropic stress conditions, is the same order of magnitude as that reported from shear splitting on the log data.

The logs are responding to accumulated strain in the material

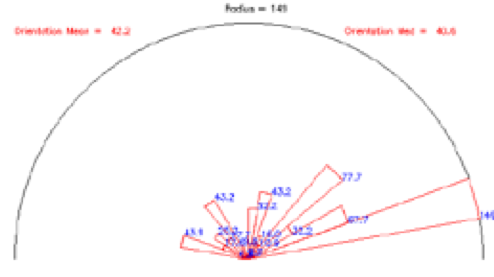
Azimuthal Anisotropy Measured Sub-Salt



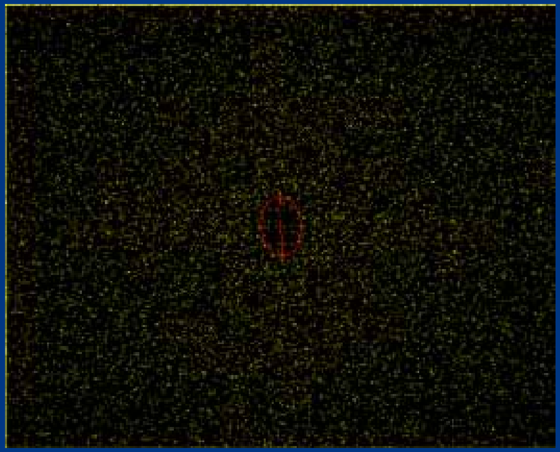
Normalized contact length in end trim thin section



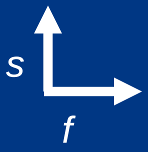
Normalized grain orientation in end trim thin section



Normalized grain fracture orientation in end trim thin section

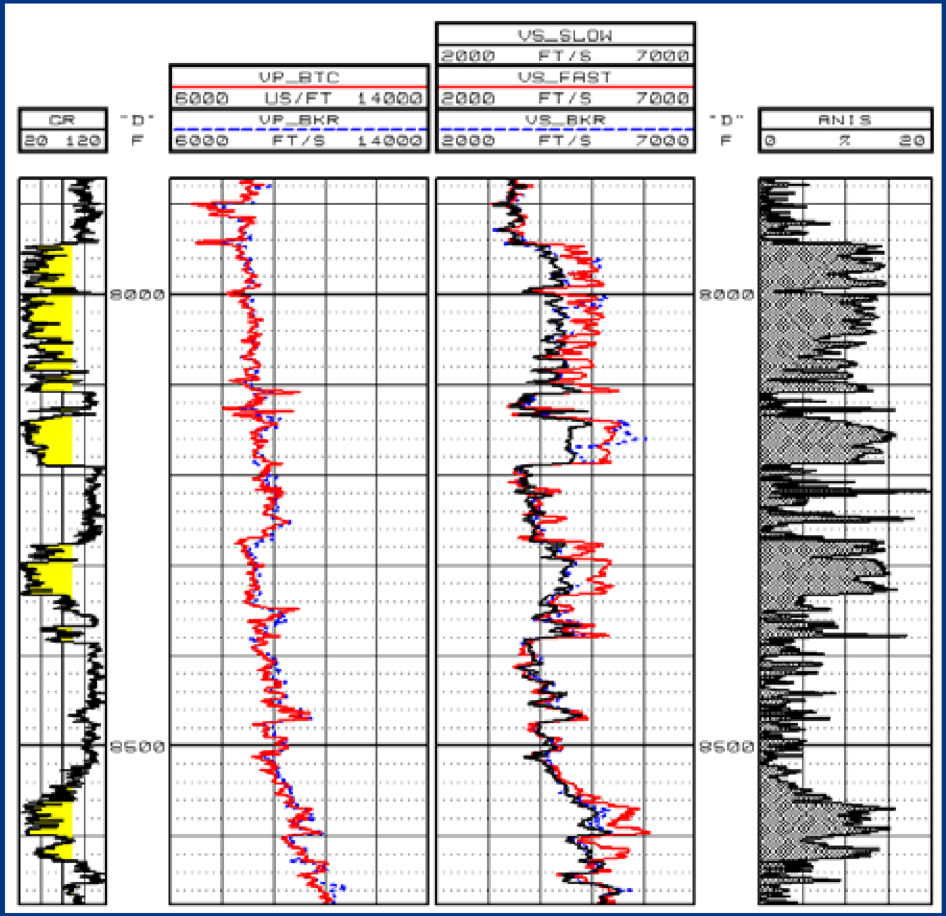


Grain Contact% = 14.2



- In this sub-salt setting, laboratory measured azimuthal acoustic anisotropy averages 9.5%.
- Note that grain contact orientations, and grain long axes, tend to be aligned perpendicular to the fast direction.
- Normalized fracture long axes are oriented perpendicular to the slow direction
- The strain ellipse from Fry analysis shows significant shortening parallel to fast direction.

Azimuthal Anisotropy Measured in Thrust Belts

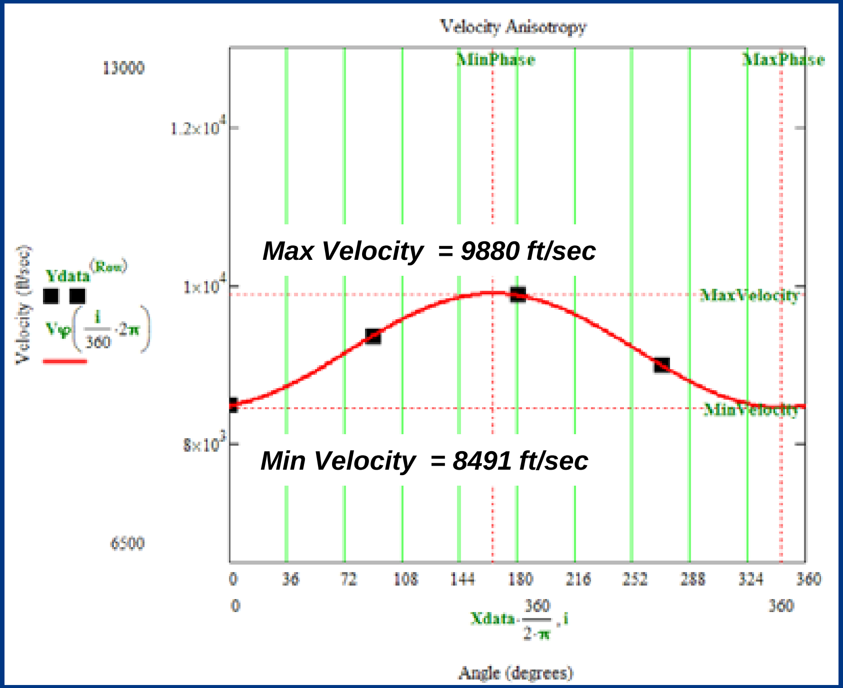


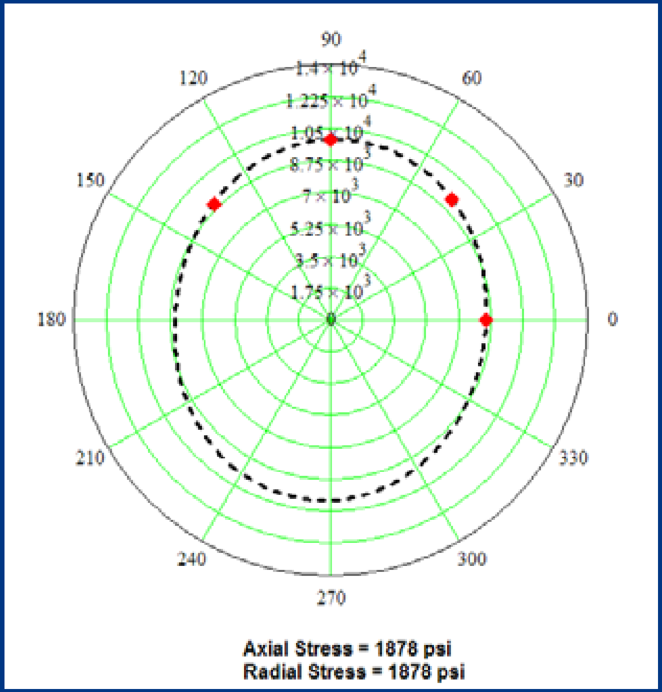
In this vertical well we see shear anisotropy in the sands.

The polarization of the faster wave is inferred to be aligned with the regional stress field.

Shear splitting suggests that the "stress-induced" anisotropy in the sands is on the order of 15%

Azimuthal Anisotropy Measured In Thrust Belts



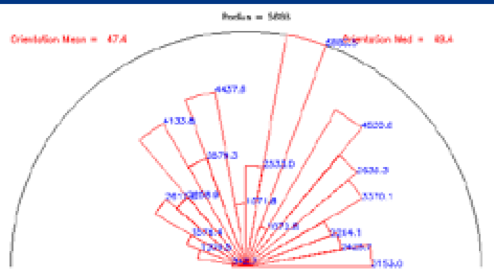


Anisotropy based on azimuthal velocities = (9880/8491) - 1 = 0.16

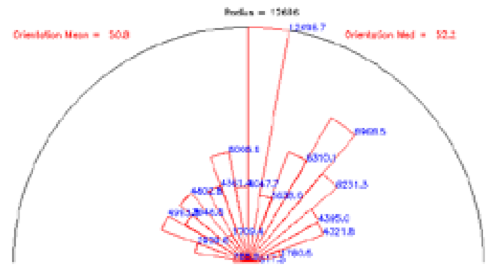
Note that this value, measured under isotropic stress conditions, is the same as that reported from shear splitting on the log data.

The logs are responding to accumulated strain in the material

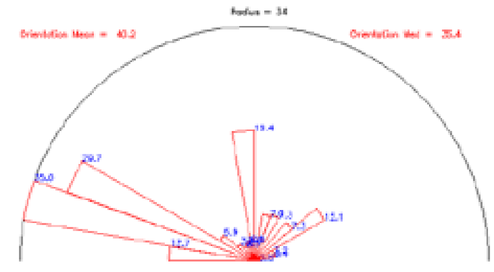
Azimuthal Anisotropy Measured In Thrust Belts



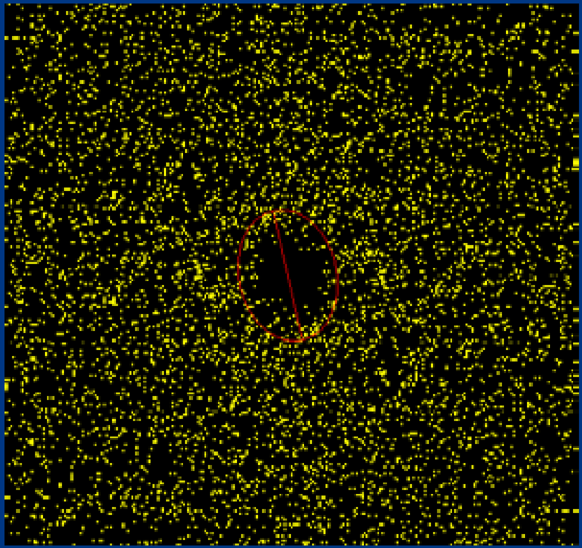
Normalized contact length in end trim thin section



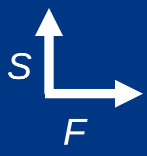
Normalized grain orientation in end trim thin section



Normalized grain fracture orientation in end trim thin section

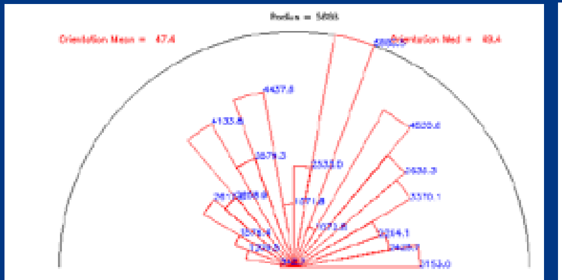


Grain Contact% = 15.6

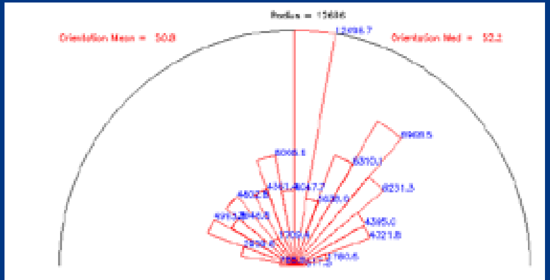


- **In this thrust belt setting, laboratory - measured azimuthal anisotropy averages 15%.**
- **Note that grain contact orientations, and grain long axes, tend to be aligned perpendicular to the fast direction.**
- **Normalized fracture long axes are oriented nearly perpendicular to the slow direction**
- **The strain ellipse from Fry analysis shows significant shortening parallel to fast direction.**

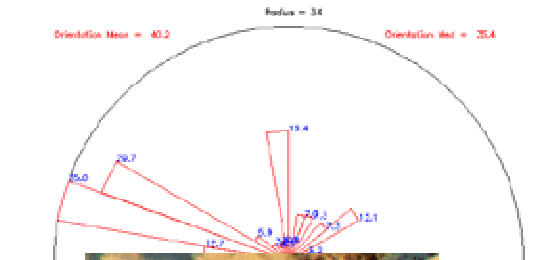
Azimuthal Anisotropy Measured In Thrust Belts



Normalized contact length in end trim thin section



Normalized grain orientation in end trim thin section



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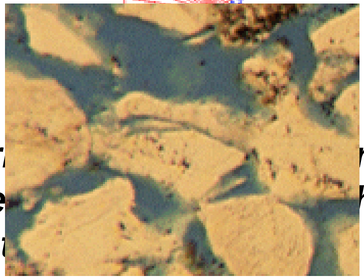

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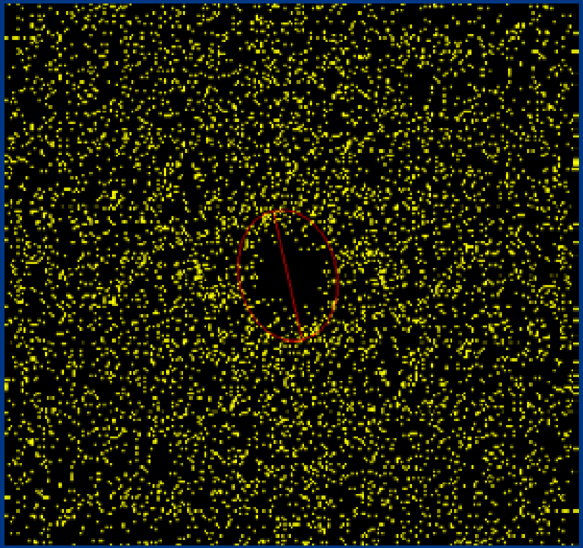
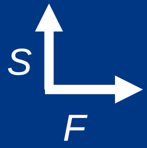
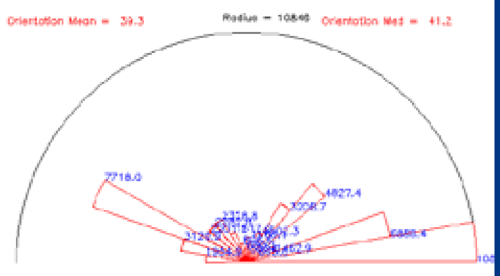


Grain Contact% = 15.6



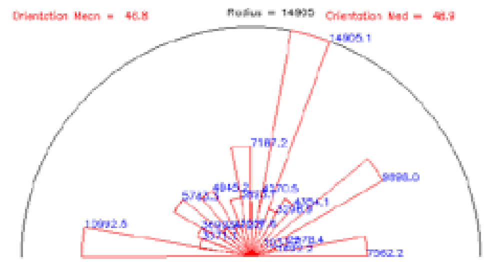
- In this thrust belt setting, laboratory - measured azimuthal anisotropy averages 15%.
- Note that grain contact orientations, and grain long axes, tend to be aligned perpendicular to the fast direction.
- Normalized fracture long axes are oriented nearly perpendicular to the slow direction
- The strain ellipse from Fry analysis shows significant shortening parallel to fast direction.

Azimuthal Anisotropy Measured In Thrust Belts

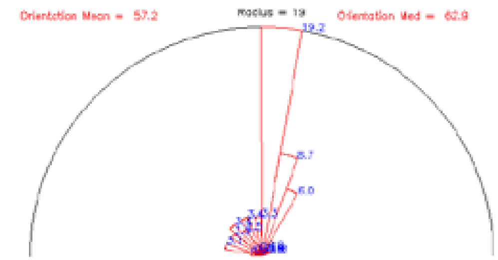


← *Bedding Direction* →

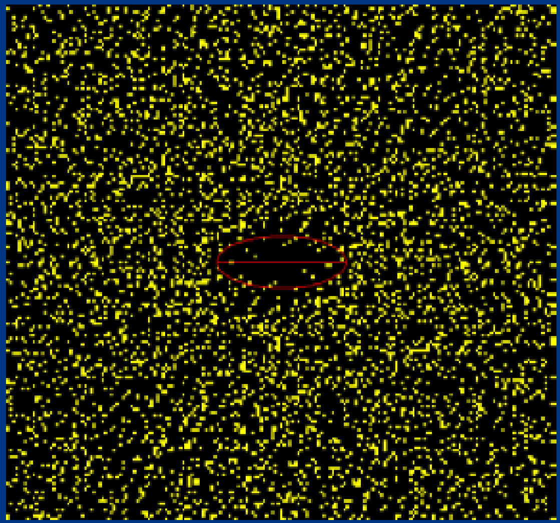
Normalized contact length in slow direction thin section



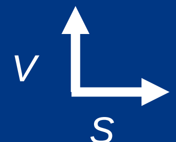
Normalized grain orientation in slow direction thin section



Normalized grain fracture orientation in slow direction thin section

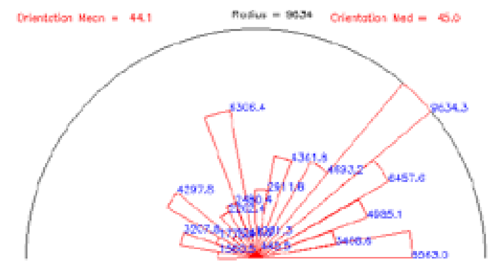


Grain Contact% = 14.8



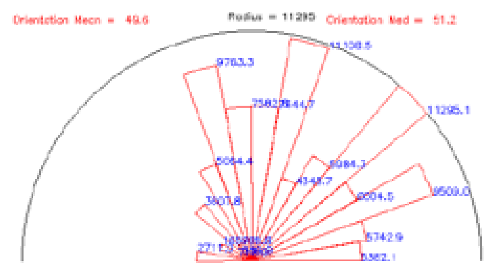
- **Note that grain contact orientations are in the bedding plane, parallel to the slow direction.**
- **Normalized grain long axes are variable, with a significant fraction in the bedding plane**
- **Normalized fracture long axes are oriented perpendicular to the slow direction**
- **The strain ellipse from Fry analysis shows significant vertical shortening resulting from normal compaction.**

Azimuthal Anisotropy Measured In Thrust Belts

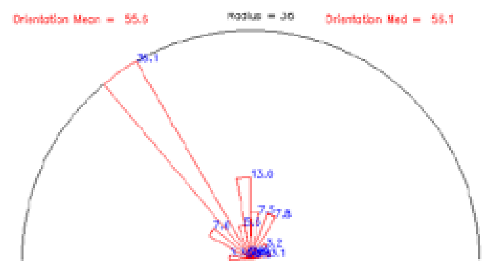


← *Bedding Direction* →

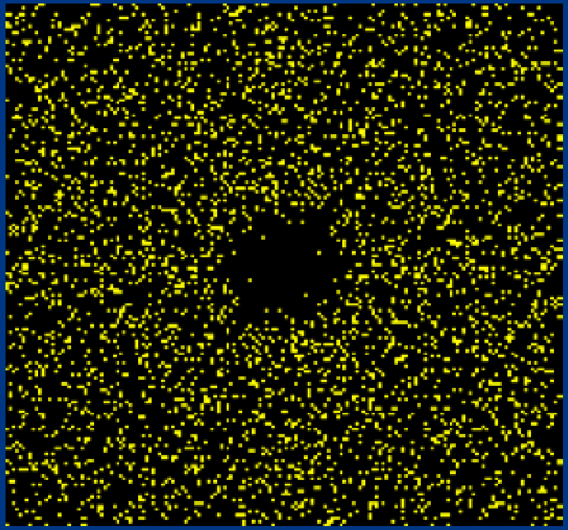
Normalized contact length in fast direction thin section



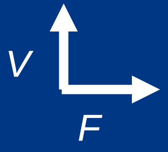
Normalized grain orientation in fast direction thin section



Normalized grain fracture orientation in fast direction thin section



Grain Contact% = 16.1



- **Note that grain contact orientations and grain long axes are rotated out of the bedding plane as compared to the slow direction**
- **Normalized fracture long axes are oriented at a high angle to the fast direction**
- **The strain ellipse from Fry analysis is a circle in the fast direction suggesting that horizontal and vertical compaction are of the same order of magnitude.**

Conclusions

•For normally consolidated sands, azimuthal anisotropy is nearly zero. Polar anisotropy is substantial, however, even in first cycle basins and at relatively low effective stresses. A TI medium is an appropriate assumption.

•In sub-salt settings, horizontal stress gradients can result in the development of significant azimuthal anisotropy (averaging nearly 10% in this example). Polar anisotropies are low, possibly reflecting the low density of the overlying salt and less well developed vertical compaction textures. A TI medium assumption may be inappropriate.

•In thrust belt settings with onset of elevated horizontal stresses while sands are still unconsolidated, azimuthal anisotropies averaging 15% (and as high as 30%) are observed. Polar anisotropies can be substantially lower than azimuthal values. A TI medium assumption may be inappropriate.

Conclusions

- Sands displaying azimuthal anisotropy under isostatic laboratory conditions have characteristic textural features.
    - Grain contacts tend to be oriented perpendicular to the fast direction
    - Grain fractures tend to be oriented perpendicular to the slow direction

- Laboratory measures of acoustic anisotropy are in good agreement with estimates from log data.

- Standard interpretation of log data (shear splitting results from stress anisotropy) may be inappropriate in these settings. Logs may be responding to accumulated strain in the material after deforming stresses have relaxed.

- Strain analysis of oriented thin sections shows that the degree of horizontal compaction in thrust belts can be as high as compaction resulting from vertical stresses.

- Accumulated strain in the sands is independent of structural position (whether on the crest or flank) but can be elevated proximal to sub seismic faults.

Future Work

- Build predictive models for horizontal compaction in thrust belt and sub-salt settings.

- Assess the variability of layer parallel compaction along the strike of thrust systems.

- Incorporate detailed textural observations into existing staged effective medium model for acoustic properties.

- Examine the influence of variable volumes of ductile grains on anisotropy development.

- Perform virtual cementation experiments to probe the influence of cement precipitation on acoustic anisotropy in these materials.