Shear-Wave Anisotropy Study using Shallow Seismic Reflection Data at the Climax Stock, former Nevada Test Site

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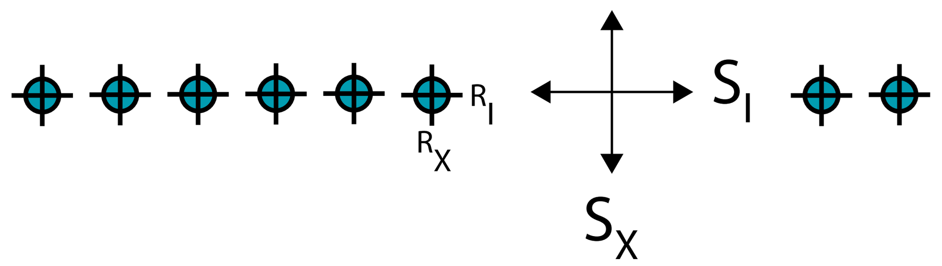
Abstract

The Climax Stock, a Cretaceous granitic (quartz monzonite) body located on the Nevada National Security Site (NNSS, formerly the Nevada Test Site) hosted three underground nuclear tests in the 1960s. Seismic recordings of these tests were characterized, in part, by anomalously high-amplitude shear waves. Several hypotheses exist as to how shear waves are generated by explosions, which, in theory, are purely compressive sources. The possible sources of shear waves include interaction with the free surface and spall, tectonic release, scattering at local velocity heterogeneities, and bulk rock velocity anisotropy. We investigated the latter hypothesis by characterizing seismic velocity anisotropy of the Climax Stock. We conducted a 9-component seismic survey (vertical and dipole shear vibration source recorded by 3-component sensors). The 288-channel survey consisted of 96 3-component receiver locations, spaced at 5-meter intervals, recording 96 3-component "mini-vibe" sources, spaced between each receiver location. These data allow us to find both the magnitude of shear-wave anisotropy and its dominant azimuth. The results of this effort will be combined with those of other experiments conducted under the Source Physics Experiments (SPE) series of explosives tests at the NNSS. A goal of the SPE is to study all aspects of shear-wave generation.

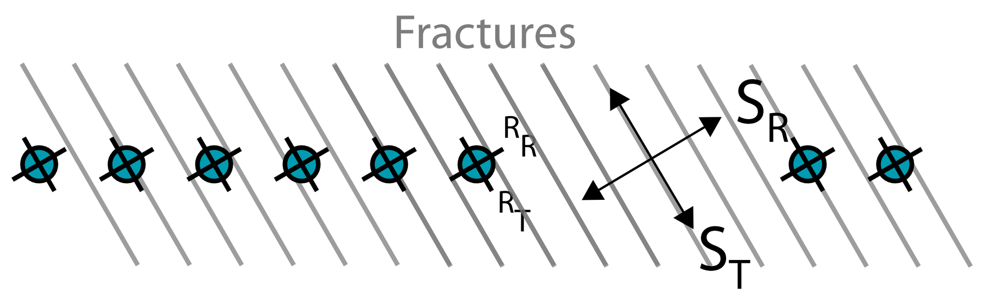
Theory

Nine-Component (9C) seismic data comprises three source orientations (vertical and orthogonal horizontal shear (S_I and S_X)), and three receiver orientations (vertical and orthogonal horizontal (R_I and R_X)). For a 2D linear survey, the shear sources and receivers are typically aligned inline and crossline with the trend of the acquisition line.



Field Coordinates

In the presence of shear-wave velocity anisotropy (aka birefringence), these field coordinates are not optimal as they lead to splitting of s-waves into "fast" and "slow" arrivals, complicating seismic interpretation. When this birefringence is caused by vertical fractures (horizontal transverse anisotropy, HTI), the dominant azimuth of the fractures can be found. This occurs when data and sources in field coordinates are rotated to "natural" coordinates, parallel and perpendicular to fracture strike. At this azimuth energy is minimized on cross-terms and maximized on alike terms.



Natural Coordinates

Theory cont.

Rotation into natural coordinates is accomplished though a process known as Alford Rotation. Alford Rotation can be thought of as acting on field data by rotating sources counter-clockwise while simultaneously rotating receivers clockwise though some angle. For field data V, rotation matrix R, and natural data U...

Rotation Matrix $$\bar{R}(\theta) = \begin{vmatrix} cos(\theta) & sin(\theta) \\ -sin(\theta) & cos(\theta) \end{vmatrix}$$

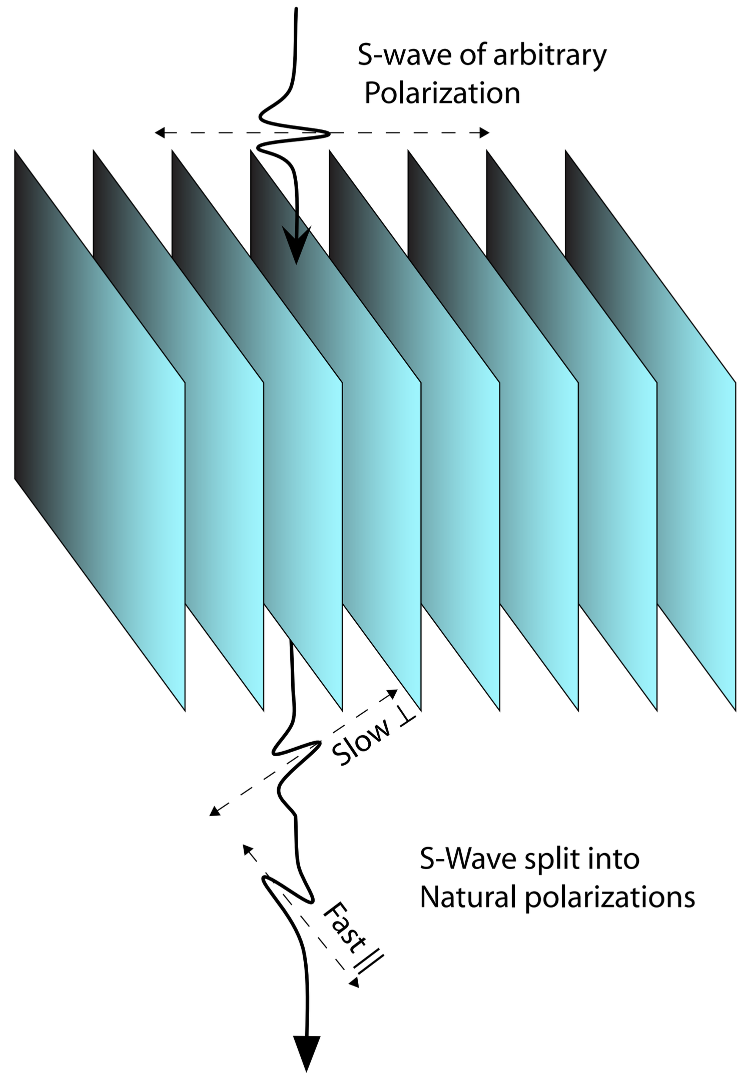
Field Coordinate Data $$\bar{V} = \begin{vmatrix} V_{XX} & V_{IX} \\ V_{XI} & V_{II} \end{vmatrix}$$

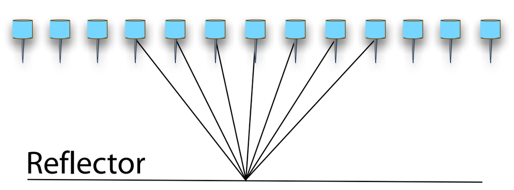
Alford Rotation $$\bar{U} = \bar{R}(\theta)\bar{V}\bar{R}^T(\theta)$$

$$\bar{U} = \begin{bmatrix} cos^2(\theta)V_{XX} + sin^2(\theta)V_{II} + \frac{sin(2\theta)(V_{IX}+V_{XI})}{2} & cos^2(\theta)V_{XI} - sin^2(\theta)V_{IX} + \frac{sin(2\theta)(V_{II}-V_{XX})}{2} \\ cos^2(\theta)V_{IX} - sin^2(\theta)V_{XI} + \frac{sin(2\theta)(V_{II}-V_{XX})}{2} & cos^2(\theta)V_{II} + sin^2(\theta)V_{XX} - \frac{sin(2\theta)(V_{IX}+V_{XI})}{2} \end{bmatrix}$$

Natural Coordinate Data

For subsurface reflection data excited and recorded on the surface, the zero-offset geometry is shown below.

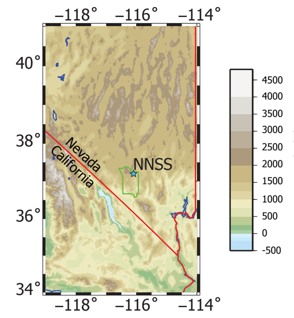




Near-Source CMP Stack

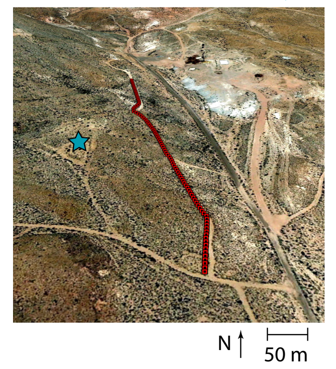
To simulate this geometry of vertically-propagating waves, we compute a common midpoint (CMP) stack of near-offset source receiver pairs. For near-offset pairs, stacking velocity is not a particularly sensitive parameter, and the increased fold will reduce uncorrelated noise.

Experiment



The Nevada National Security Site is located in southern Nevada. Field area is indicated by the star.

Line Geometry



Red squares are receiver locations. A 3-C vibrator source is located between each receiver location. The blue star is the location of a raised-bore drill rig, in concurrent operation.

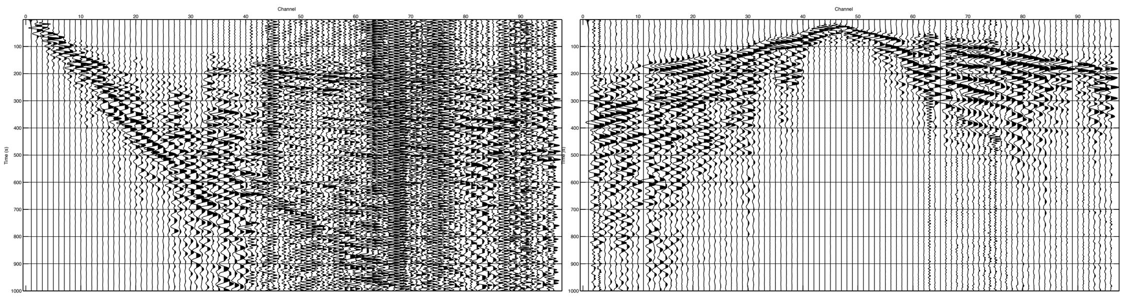
Acquisition Settings

Parameter	Value
Geophones	96 3-Comp 4.5 Hz
Recorders	12 Geometrics Geodes
Sources	96 IVI 3-C Vibe Locs
Receiver Spacing	5 Meters
Source Spacing	5 Meters
Sweep Length	20 Seconds (20 – 220 HZ)
Sample Interval	1 Millisecond
Listening Time	3 Seconds
Stacks	5

Fun weather

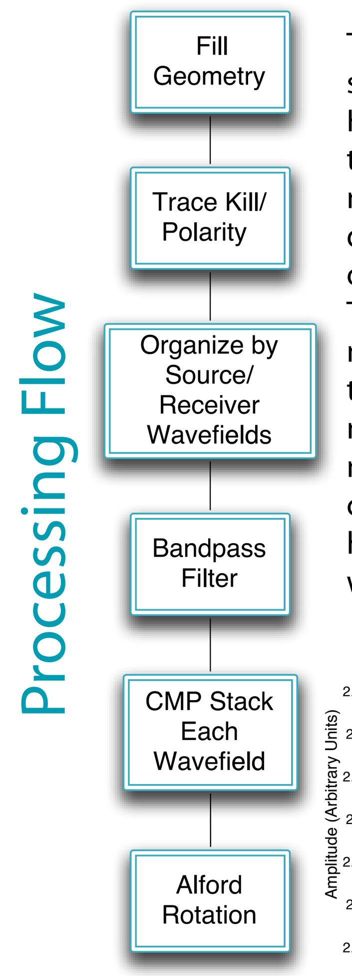
IVI Mini-Vibe

Due to drilling delays, a schedule conflict arose such active drilling was commencing 100 meters from the line. There were two types of drilling ongoing at the site: drilling for depth with a hammer drill, and reaming of the hole after total depth was reached. Hammer drilling rendered anything other than first break picking impossible. Reaming was less noisy.

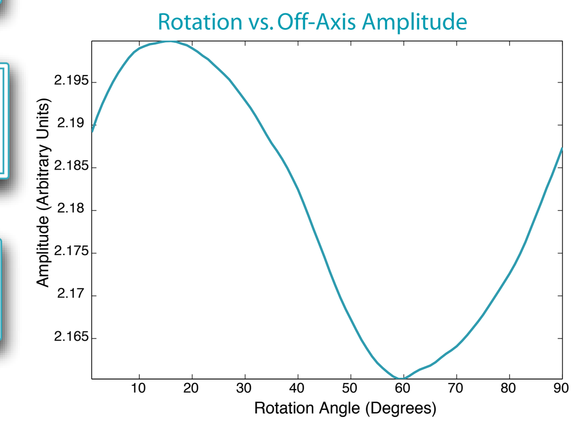


Particularly Noisy Record (Hammer Drilling) — Less Noisy Record (Reaming)

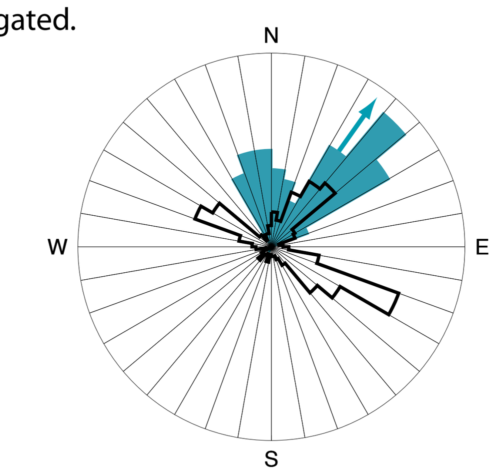
Results



Two main difficulties presented themselves when processing the data. 1) High-amplitude reflections are rare in this data set as the Climax Stock quartz monzonite seems fairly uniform with depth; and 2) the noise from the drill rig obscured any low-amplitude reflections. The use of near-source CMP stacking mitigated these difficulties somewhat as the vibrator strength is at a maximum near the source. The other way to maximize signal-to-noise ratio was to concentrate the analysis on the upper few hundred milliseconds of the record, where signal strength was at its greatest.



The figure above plots the energy of all 96 off-axis CMP stack components versus rotation angle. This was computed via the sum of the square root of amplitude squared. The orientation of the fractures is parallel to the acquisition when this value is minimized (at 59 degrees rotation here). If this holds true, then the fractures are oriented N34E, since our field coordinates are oriented N15W. The overall reduction of energy at the optimal rotation angle is only around 2%, which suggests that the magnitude of anisotropy is small, however. The rose diagram below plots the optimal rotation angle of each of the 96 CMP traces (blue bars) and the dip angle plus 90 degrees of high-angle fractures mapped in boreholes 100 meters from the line (black bars). The blue arrow is the N34E value from averaging all CMPs. As can be seen, the rose diagram shows a bimodal distribution which suggests that fractures do not have a consistent azimuth along the line. This is currently being investigated.

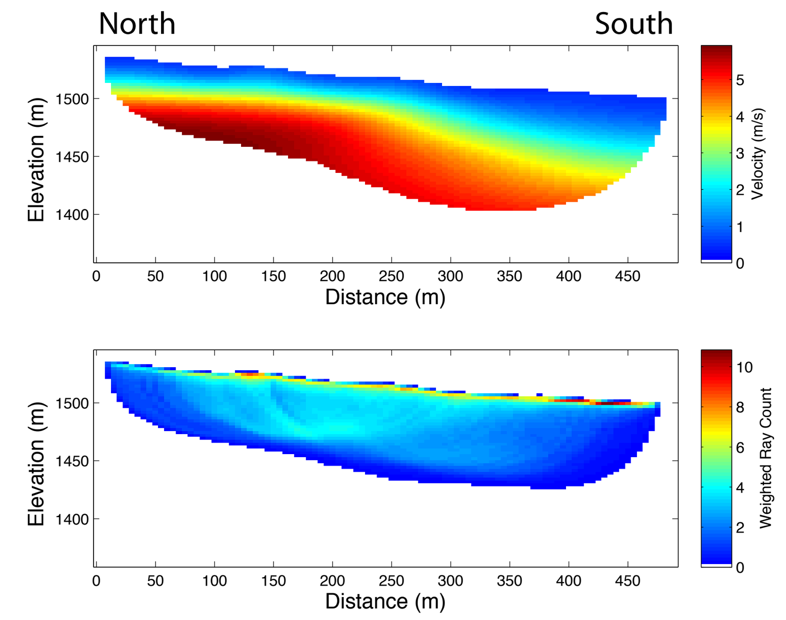


Blue: Alford Azimuth
Black: Borehole Fracture Dip +90 deg

Results

We also computed P-wave velocity tomograms using an internal 3-D finite difference ray-tracing algorithm. Due to the drilling, first break picks were weighted, with greater weights given to nearer offsets. The site is characterized by velocities consistent with decomposed granite or sand at depths shallower than 5 meters in the north end, rapidly transistioning to intact granite velocities below that. This velocity information will be used in the future to stack and migrate the reflection data.

P-wave Refraction Tomography



Conclusions

1) Alford rotation of 9-C data at the Climax Stock site yields natural coordinates consistent with the azimuth of one set of fractures mapped in an adjacent borehole.

2) Anistropy appears to be weak in that the overall reduction in off-axis energy at optimal rotation angle is only appoximately 2 percent. Borehole mapping shows two orthogonal sets of vertical fractures. If the effect on seismic waves of these fractures is more or less equal, this behavior may be expected, as media is no longer HTI and is orthorhombic. This will be modeled in the future.

3) The rotation angle is not consistent along the entire 475 meter line, indicating inconsistent fracture azimuth, or poor signal-to-noise data.

4) Noise from adjacent drilling and low-amplitude reflections in granite combined to make interpretation difficult.

Acknowledgements

Bob White and Ryan Emmitt of NSTec helped with the fieldwork. The IVI Mini-Vibe was rented from UNLV and operated by Chris Cauthron. Fractures were mapped by NSTec staff and summarized in a report written by Lance Prothro.

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