Seismic Anisotropic Resolution

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Summary

What is seismic anisotropy and how does it affect exploration and processing? This question has been addressed with increasing frequency in the past few decades, but its origins go back much further. The earth has always been anisotropic, but it has been assumed isotropic during the earliest parts of geophysical exploration. Only when newer surveying methods and better data quality necessitated higher processing accuracy did seismic anisotropy get much attention. Since then there has been an upsurge in research done and discoveries made in the field. Now, anisotropic corrections are all but required for processing seismic data, and entirely new methods have been created to exploit unique aspects of anisotropy. It is understood that anisotropy occurs in many ways and on many different scales. What is important to know is that different scales of seismic waves may experience different levels of anisotropy. This is an issue I would like to investigate.

History

Helbig and Thomsen (2005) produced a well written history of anisotropy, of which I will focus on major events and issues relating to seismic anisotropy. Seismic anisotropy began with Maurice Rudzki, The first official professor of geophysics, in 1895 and he was certain of the anisotropy of rocks. He solved the wavefront of transversely isotropic (see figure 1) and orthorhombic media in 1911, and wrote about surface waves in transverse isotropy in 1912. He also discussed Fermat's principle for anisotropic media. Rudzki passed away in 1916, and with him passed much interest in seismic anisotropy. For 60 years research into seismic anisotropy stagnated. There were few papers published between 1920 and 1950 about anisotropy and most of those were investigations and measurements of velocities in anisotropic rocks. There were a few years in the mid 1950's where half a dozen papers on layered anisotropy were written by various authors. But again, interest waned shortly thereafter.

Interest in seismic anisotropy regained momentum in the mid 1970's when Indra Gupta and later Stuart Crampin wrote about azimuthal anisotropy. This type of anisotropy can be caused by cracks preferentially opening parallel to the direction of greatest stress in a rock. This concept was unique for the time in that it described how otherwise isotropic rock became anisotropic, and because it gave a direct method to characterize hydrocarbon reservoirs. In 1986 Leon Thomsen published the seminal article *Weak Elastic Anisotropy* in which he attributed parameters for describing anisotropy in a medium. While these parameters are intended to describe weak anisotropy, they are readily used for all degrees of transverse isotropy, and have been extended for use in orthorhombic, monoclinic and triclinic symmetries (Tsvankin et al., 2010).

Richard Alford, in 1986, solved a problem encountered in early SH wave surveys. In anisotropic media, the polarization of the shear waves is not determined by the source. Instead, any shear waves input to the ground are immediately split along the fast and slow axes of the media in a process called shear wave splitting. For azimuthal anisotropic media, if the receiver is not in line with one of these directions then both shear waves appear on each horizontal trace. This confounded the early SH surveys. Alford's solution was to shoot both SH and SV surveys and capture data on both horizontal components. He then created a matrix of the data which could be rotated to isolate each type of shear wave (see Figure 2). A simple extension of Alford's concept was used in 1988 by Robert Garotta and Pierre-Yves Granger to determine the principle axes of the azimuthal anisotropy.

Developments in seismic anisotropy continue today, and most build upon the framework laid down by prior discoveries. As such, many new concepts are more incremental or extensional in nature, but still share equal importance with their earlier counterparts.

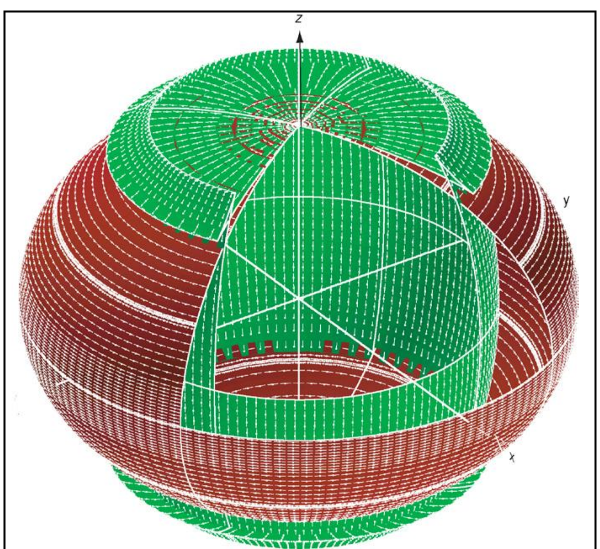

Figure 1: Wavefronts for polar anisotropy (SH in red, SV in green). Note the triplication in SV near 45°. (Reprinted from Helbig and Thomsen, 2005)

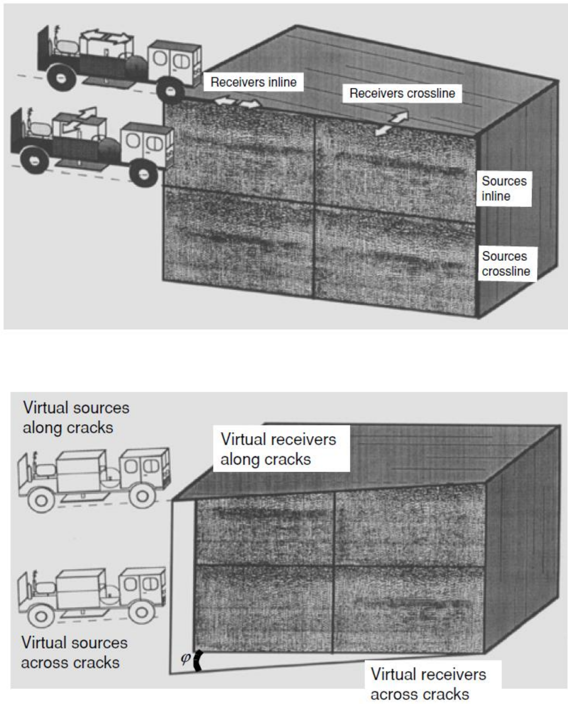

Figure 2: 2x2 matrix of seismic data. The top frame shows what the raw data would look like after stacking and preprocessing. If this media were isotropic then the bottom left square should contain no signal, only noise. The bottom frame shows the data rotated to be in line with the principle axes of azimuthal anisotropy. The polarization of the shear waves at the source are now able to pass through the media without splitting, resulting in no data on the upper-right and lower-left squares. (Reprinted from Helbig and Thomsen, 2005)

Concepts and Methods

Anisotropy is the variation of a feature with angle, for seismic anisotropy this is velocity. The two basic types of anisotropy are polar and azimuthal (Thomsen, 2001). Polar anisotropy, also known as transverse isotropy, gets its name from its radial symmetry. Velocity varies along the vertical axis compared to the symmetry plane. This axis can be oriented in many directions. If it is orthogonal to the ground then the symmetry is described as vertical transverse isotropy (VTI). Similarly, if it is parallel to the ground it is called horizontal transverse isotropy (HTI). Titled transverse isotropy (TTI) occurs when the axis normal to the symmetry plane is not horizontal or vertical. The other form of anisotropy occurs when the velocity variation depends on its angle from North, and is appropriately called azimuthal anisotropy.

All anisotropy is caused by the uniform alignment of some feature, called preferred orientation. These features can be of any size. On the smallest scale, the preferred orientation of mineral grains can cause anisotropy. Shales are inherently anisotropic because of their physical makeup. Shales are made of plate like grains that are typically compacted and ordered, like a deck of cards. They also undergo temperature induced chemical diagenesis whereby smectite transforms into ordered illite (Vernik and Liu, 1997). Both of these effects combine to make shale anisotropic. Another very common occurrence of grain dependent anisotropy is in the mantle. Mantle convection reorients olivine grains (which are inherently anisotropic) such that their fast axes are aligned with the direction of flow. Beneath mid-ocean ridges the mantle convects upwards, then diverts and travels perpendicular to the mid-ocean ridge under the oceanic crust. This creates large scale azimuthal anisotropy of the mantle under the oceans, with Velocities being faster orthogonal to mid-ocean ridges (Lappin, 1971). The olivine grains in the mantle are oriented by vast strain fields, but stress/strain fields don't need to move mineral grains in order to induce anisotropy. The simple presence of the field is enough to create anisotropy in a region. Anisotropy has been associated with the deforming stress from sea floor subsidence caused by a reservoir collapse (Tsvankin et al., 2010).

In the shallow earth anisotropy is more often caused by layering or fractures. Layering occurs on many scales. Foliations and fissility in rocks create small scale anisotropy. These are most evident in shales. Bedding planes and interbedded materials create anisotropy on mesoscales, while series of parallel layers creates large scale anisotropy. Layering typically causes VTI, or TTI if the layers are not horizontal. Fractures create anisotropy when they are preferentially aligned, since velocities are lower when travelling perpendicular to the crack face (Owens and Bamford, 1976). In rocks with high degrees of cleavage, most cracks that form will be aligned in those planes, creating anisotropy. Some rocks have multiple sets of aligned fractures. These fracture sets can be orthogonal or have arbitrary orientation to each other, and in either case complex anisotropic fields will form, usually orthorhombic (Schoenberg and Sayers, 1995). Even rocks with randomly oriented cracks can show signs of anisotropy when a uniform stress is applied. Cracks oriented parallel to the direction of maximum stress will stay open, while other cracks will close. This gives the effect of only one set of oriented fractures (Owens and Bamford, 1976).

Porosity can cause anisotropy in two ways. If a rock contains high aspect ratio pores which are preferentially aligned, then anisotropy will form. For example, a carbonate with a large amount of vuggy porosity will be anisotropic if most of its pores are horizontal (i.e. from layering of shells). Anisotropy would occur regardless of the distribution of the pores, it is solely an effect of their orientation. Even rocks with circular pores will display anisotropy if the pore distribution is anything but random.

Seismic anisotropic resolution

Anisotropic Resolution

The most important factor for determining anisotropy is scale. For anisotropy to exist, the wavelength of the seismic wave must be much larger than the size of the oriented features. This size can vary greatly, from millimeter scale for oriented grains to tens of meters for layer induced anisotropy. This means that certain wavelengths will be able to "see" different anisotropy scales. For example, a middle frequency may experience grain induced anisotropy, but not layer induced anisotropy. Approximate order of magnitude scale for different types of orient-able features:

scale [m]	oriented feature
100	massive layer
10	layer
1	thin bed
0.1	bedding plane
0.01	foliation
0.001	mineral cleavage
0.0001	sand sized grain
0.00001	
0.000001	clay sized grain

This shows the complex nature of anisotropy, since many scales of anisotropy can affect any given material. Below is a list of frequencies for varying seismic survey methods, taken from the *Geophysical Data Processing* class taught by Dr. Liner in the spring of 2011:

frequency range	seismic type
10-100 Hz	surface seismic
20-300 Hz	vert. seismic profile
300-1200 Hz	Cross-well seismic
15-20 KHz	sonic log
1-4 MHz	ultrasonic

The calculation of the wavelength for a seismic wave at the different frequencies represented above is not a straightforward process. Since rocks are dispersive, choosing one velocity at which to calculate the wavelength over all frequencies is inappropriate (Sams et al., 1997), and can result in errors of 10% in wavelength (see table 1) Therefore a frequency dependent velocity model must be used. Kjartansson (1979) describes the relation between phase velocity and frequency using his constant Q theory:

$$v = v_0 \left|\frac{f}{f_0}\right|^{\gamma}$$

$$\gamma = \frac{1}{\pi}\tan^{-1}\left(\frac{1}{Q}\right)$$

Where v is the frequency dependent phase velocity, f is frequency in Hertz, and Q is the attenuation of the medium. v_0 and f_0 are the reference velocities and frequencies. The values in use here are $v_0 = 3500\, m/s$, $f_0 = 20\, KHz$ and $Q = 25$, which are consistent with the findings of Sams et at. (1997) for intrinsic attenuation. Wavelength is now calculated by $\lambda = v/f$, for all frequencies, using the dispersive velocity from Kjartansson's constant Q theory.

According to the effective medium theory if a wave passes through an inhomogeneous medium and its wavelength is much greater than the components of the medium, then the medium can be considered effectively homogeneous. The properties of the medium will be some combination of the properties of its components. In our case the medium will be considered anisotropic. I shall assume that the wavelength must be five times longer than the scale of oriented features in order to be considered effectively homogeneous (anisotropic). The results of this comparison can be seen in Figure 3. An example for clarification: consider a vertical seismic profile consisting of only 200 Hz signal passing through a layered medium, with thin-beds, bedding planes, and anisotropic grains. Using the Constant Q theory the velocity is calculated as 3300 m/s, and the wavelength is 16.5 meters. Any oriented feature set spaced less that 16.5/5= 3.3 meters apart will be considered effectively homogeneous (anisotropic). Thus, the thin beds of meter thickness, the bedding planes of decimeter thickness, and the grains of millimeter thickness will all contribute to the anisotropy. The regular layers of 10 meter spacing will not be effectively homogeneous. Instead the 200 Hz wave will pass through them according to Snell's law.

Applications

Seismic anisotropy was excluded from processing for many years. Disregarding seismic anisotropy was possible because most data acquired were from short offset surveys (less than 30°), mostly P-wave surveys were performed, and the overall data quality did not require it (Helbig and Thomsen, 2005). This has changed in the past few decades. Much longer surveys are performed, as well as 3-D and multi-component surveys. Data quality are much improved

Frequency [Hz]	v(f) [m/s]	λ(f) [m]	λ(v=3500 m/s) [m]	Change in λ (m)	% change
10	3177.32	317.73	350	32.27	9.22
1000	3369.08	3.37	3.5	0.13	3.74
15000	3487.21	0.232481	0.233333	0.000853	0.37
2000000	3711.24	0.001856	0.00175	0.000106	6.04

Table 1: comparison of velocity and wavelength between a dispersive and constant velocity medium. In wide frequency analysis, the use of a constant velocity medium results in errors in wavelength up to 10%.

as well, and the simple assumptions made in the past are no longer good enough (Tsvankin et al., 2010). Anisotropy affects all aspects of processing. For example, depth misties occur between PP-wave and PS-wave data in anisotropic zones (Tsvankin et al., 2010).

The identification of the type and degree of anisotropy is thus very important for correct data processing. In a 3-D survey, direct P-wave arrivals can easily be used to find azimuthal velocity variation. Anisotropy can also be detected using a phenomenon called shear wave splitting. When a shear wave enters an anisotropic medium it will split in two. One wave will polarize itself along the slow axis of the medium and the other to the fast axis (Liu et al., 1989). Depending on the direction of travel, shear wave splitting will identify different types of anisotropy. Surface waves can also be used to detect anisotropy. Differences in arrival times between Love and Rayleigh waves taken in different directions will be a measure of azimuthal anisotropy.

There are many different applications of seismic anisotropy in geophysical exploration. At reservoir depth, most open cracks in rocks will be vertical because the overburden pressure will be much greater than the hydrostatic pressure. This will cause azimuthal anisotropy in the rocks. This anisotropy can be detected using a properly designed survey and parameters can be extracted that directly relate to reservoir characteristics. This is important to reservoir characterization studies, but can also be used for hydrocarbon exploration (Helbig and Thomsen, 2005). Anisotropy is also caused by stress fields present in the subsurface. Time lapse modeling of anisotropy in an area can indicate how stresses in the subsurface are changing (Sarkar et al., 2003). Lastly, different types of anisotropy may be resolved by using the anisotropic resolution method. Performing multiple seismic experiments at different frequencies and detecting the change in anisotropic parameters can give a rough estimate of the oriented feature size within that medium.

Conclusion

Seismic anisotropy has come a long way in the past few decades. It has gone from disregarded fact to core ideal in the exploration and processing fields. One important fact is that anisotropy can affect many scales in the earth, from properties inherent to individual grains to vast layered basins behaving in an effectively homogeneous way. The operative question before any seismic survey is, at what scale will I be sampling the earth and how will that affect the anisotropy I record?

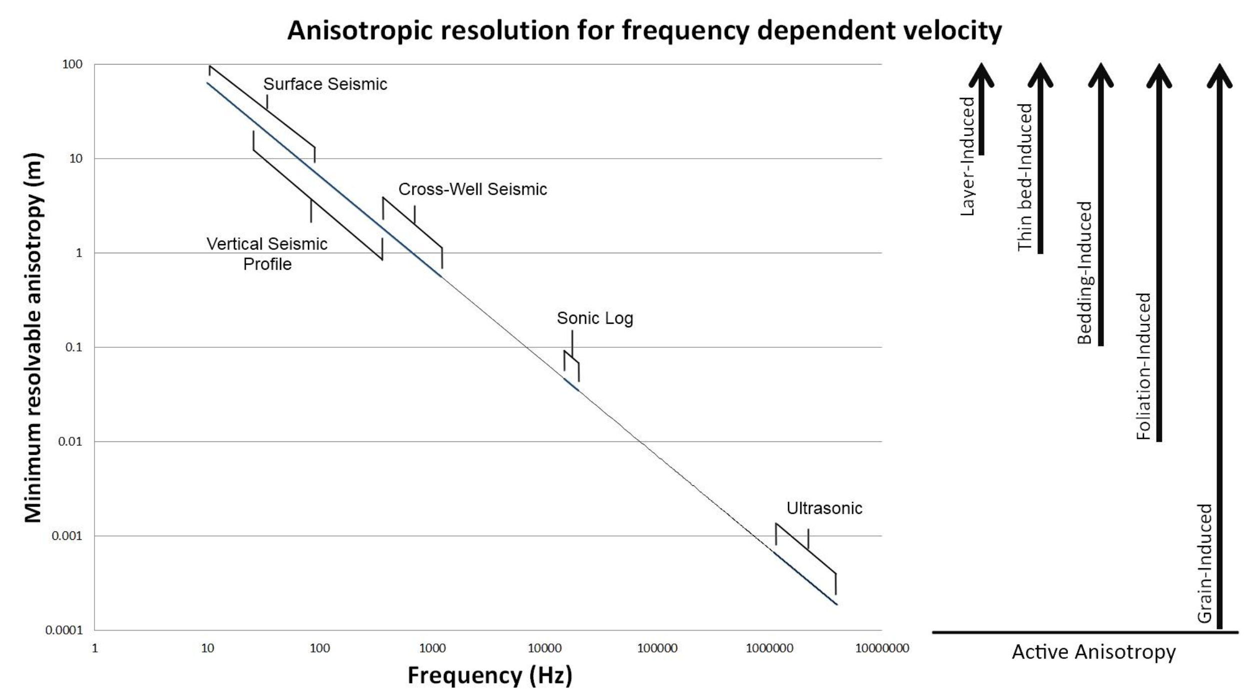

Figure 3: Effective anisotropy curve for a dispersive media. The plotted wavelength is scaled back by a factor of five to be compared to anisotropic feature sizes. The vertical axis shows scales of anisotropy, for any frequency, if the scaled wavelength is greater than the size of anisotropic features then that anisotropy will be "active." Surface seismic is affected by all types of anisotropy. Depending on frequency, VSP may not be affected by Layer-induced anisotropy, but is still affected by all others. Cross-well seismic is near the tuning frequency for thin beds, thus it may or may not be subject to that type of anisotropy. Sonic logs are affected only by foliated and grain induced anisotropy. Ultrasonic methods can only detect grain-induced anisotropy.

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