Seismic anisotropy: its types and importance

Let us begin by understanding the term *isotropy*. It is made up of two Greek words: '*iso-* ', which means equal, and '*tropikos*', which implies 'turning'. Thus, isotropic means having the same properties in all directions. If we are discussing isotropy in the context of crystals, then it could imply the velocity of light in crystals is the same in all directions. Likewise, an *anisotropic* crystal would exhibit directional properties, i.e., the property in one direction is different from the same property in a different direction. You may remember from your college minerology course that light travels at different speeds as you move away from the optical axis of crystals of calcite, quartz, tourmaline, and other semitransparent minerals. Petrophysicists use this "birefringence" along with color and crystal shape to identify the minerals under a microscope.

From crystals if we now turn to rocks, the usage of the terms isotropy or anisotropy stays the same. However, it is important to mention that the term isotropy is different from *homogeneous*, which has a reference to uniformity of composition. Lack of uniformity of composition in a rock is often called *heterogeneous*. Figure 1 illustrates the difference between the four terms mentioned above.

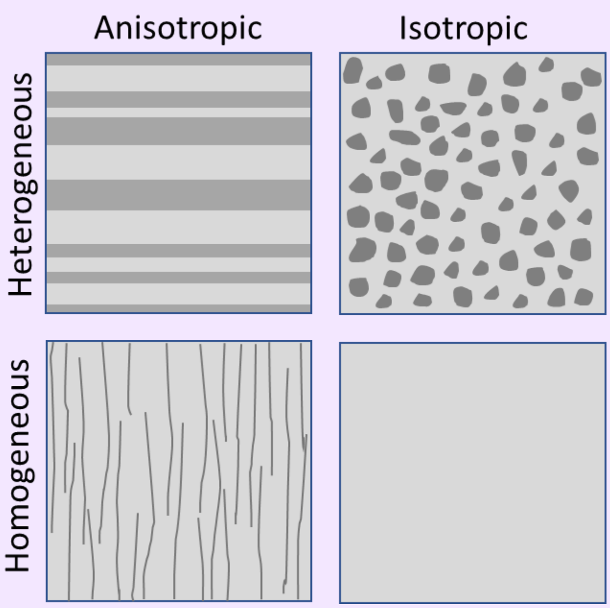

Figure 1: Illustration of the distinction between Isotropic, anisotropic, homogeneous, and heterogeneous rock samples.

The rock sample shown to the lower right is a homogeneous and isotropic material, so that any measurement of velocity of density carried out on this sample will be spatially invariant in any direction. A common example would be quartzite or micritic limestone.

The sample to the top right is isotropic but heterogeneous due to the rock fabric exhibiting a specific but consistent pattern of the rock constituent minerals. A coarse-grained sandstone cemented with a fine matrix is heterogeneous, but the pattern does not change with orientation.

The sample to the lower left is homogeneous and anisotropic. The vertical lines indicate microfractures. Even though the rock sample has uniform composition it exhibits anisotropy due to fracture orientation. In general, fine-grained shales are homogeneous and anisotropic, with the flat part of the clay minerals oriented horizontally soon after they are deposited.

Finally, the layered pattern of the rock sample shown to the top left is typical of sedimentary rocks due to their deposition mechanism, depicting two types of rocks, e.g., sandstone and limestone. Even if each of these two components are homogeneous, when taken together, the rock package is heterogeneous. If you strike an outcrop with a hammer and measure it 50 m away on the bedding plane, the energy arrives at the faster limestone velocity. In contrast if you make your measurement perpendicular to the bedding the energy needs to travel through both types of rocks, with the velocity falling between that of limestone and sandstone. Thus, the rock sample to top left is both anisotropic and heterogeneous.

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The photos for the outcrops included for each of these cases exhibit how the real rocks look, and help us understand the importance of anisotropy, as well as the need for its correction to the seismic data we analyse.

Many rock properties can be anisotropic including velocity, permeability, resistivity all of which are related to "flow" in a direction. Other properties such as density and color are always isotropic. In terms of seismic data, both compressional and shear velocities can be anisotropic. We have two kinds of anisotropy which are usually indistinguishable at the resolution of seismic data. Intrinsic anisotropy is usually associated with the orientation of the minerals that form a rock. If the anisotropic minerals align, the rock is anisotropic. In contrast, if we have a stack of alternating isotropic layers of 1 m thickness that are measured by a 30 m wavelength, we have *effective anisotropy*. The example shown in Figure 1 (top left) is now illustrated in Figure 2a, where clastic sediments (shales) exhibit what has been characterized as a symmetry class called *transverse isotropy* (TI).

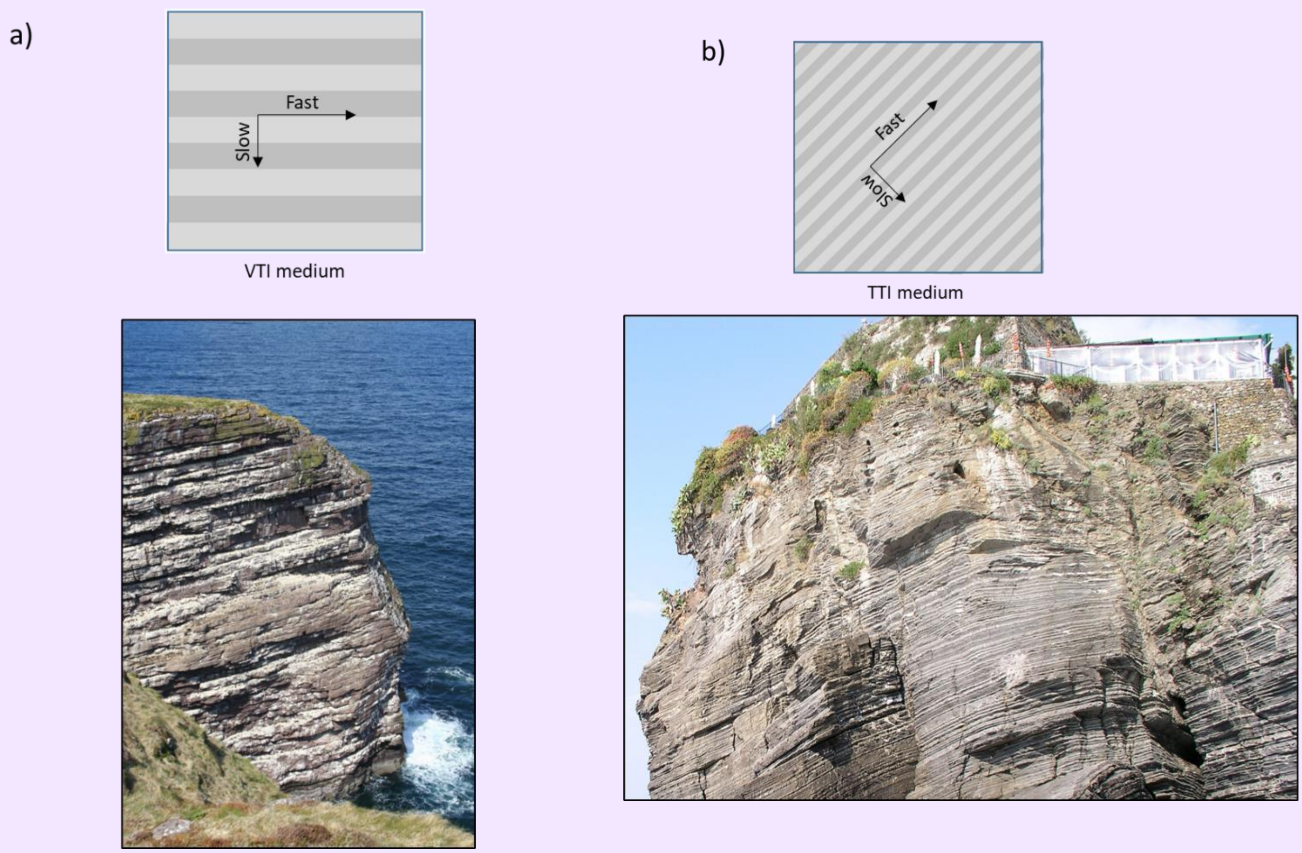

Figure 2: (a) A cartoon and photo illustrating vertical transverse isotropy (VTI) where the sedimentary strata (and platy clay minerals) are approximately horizontal.

(b) A cartoon and photo illustrating tilted transverse isotropy (TTI) where the initially horizontal sedimentary strata have been rotated through tectonic forces and/or basin subsidence. The home on the upper right provides a good estimate of the horizontal.

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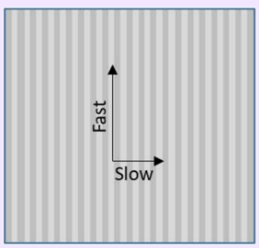
Such a medium has a vertical axis of symmetry orthogonal to the bedding of the rock. Rocks that exhibit a vertical axis of symmetry are referred to as *vertical transverse isotropy* (VTI). The velocity measurement in all directions in the plane of the bedding will be the same, but it would decrease as the angle of propagation increases with respect to the vertical direction. The thickness and velocity difference in the layers will determine the extent or the strength of anisotropy observed. VTI manifests as nonhyperbolic moveout in the far offsets in the form of 'hockey-stick' effect on NMO-corrected and isotropically migrated seismic gathers. If not corrected during processing anisotropy can lead to poor quality stacked data and thus, inaccurate interpretation.

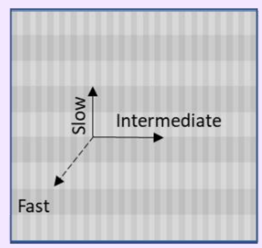
Besides the flat layered rocks that have been discussed above, frequently we also come across dipping layered strata that have their axis of symmetry tilted. Such changes are caused by basins subsidence or listric and overthrust faults. As shown in Figure 2b, such a case is referred to as *tilted transverse isotropy*, or TTI. Estimates of TTI are critical in migrating the flanks of salt diapirs, where the originally flat shales have been strongly tilted due salt withdrawal forming minibasins.

c)



HTI medium

d)



Orthorhombic

Figure 2: (c) A cartoon and photo illustrating horizontal transverse isotropy (HTI) where the initially horizontal sedimentary strata have been rotated to now be vertical. sample illustrating the case of HTI where the aligned fractures are seen in the vertical direction. If the small joints cutting the strata influence the velocity, this rock would be slightly orthorhombic, as in the next image.

(d) A cartoon and photo illustrating orthorhombic anisotropy (VTI+HTI). The photo shows relatively horizontal strata cut by two orthogonal sets of vertical fractures where the second set is represented by the near planar cliff face.

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The length of the black arrows in the cartoons is proportional to the velocity measured in that orientation. The dashed arrow in (d) is parallel to the major fracture planes, perpendicular to the plane of the paper. and oriented along the aligned vertical fractures. By Fermat's principle of least time, energy will travel along the fastest route possible, such that the velocity parallel to the layers will be the faster of the two rock units. In contrast, the ray path perpendicular to the bedding plane needs to cross both the faster and the lighter rock units, such that the resulting velocity will the harmonic average of the two velocities. If the fractures are filled with slower fluid or cement, then the faster P-wave velocity will be parallel and the slower P-wave velocity perpendicular to the fractures.

The photo in (a) is of Handa island, off the west coast of Scotland, which rise to over 100 m high and are composed of Torridonian (Proterozoic age) sandstone. The photos in (b), (c), and (d) were taken on the Mediterranean coast near Porto Venere, Liguria, Italy. The cliff exposures are predominantly of thick sandstone and claystone turbiditic rocks and are part of the northern Apennine, an orogenic chain formed during the Cenozoic era. These units were folded and faulted during the Oligocene to early Miocene epochs. (All photos courtesy: Martin Layzell, Calgary).

The presence of dipping anisotropic strata in the subsurface can lead to positioning errors, and even overlapping of the seismic reflections below, much like looking at newsprint through a calcite crystal.

The extreme case of TTI is when the rock layers have been turned vertical as in Figure 2c, where now the axis of symmetry is horizontal, perpendicular to the bedding, and named *vertical transverse isotropy* or VTI. Although vertical bedding is relatively rare, VTI is not. Because the maximum vertical stress is usually vertical, the most common orientation of fractures is vertical. There are two scales of fracture anisotropy, which look different on outcrop but the same on seismic data. The easiest to visualize are macroscopic fractures, where the geoscientist can put a finger or even a hand in cracks and joints. Harder to understand, but far more common in the unconventional reservoirs are microcracks. Although these microcracks are assumed to be evenly distributed in all orientations, it is the subset of cracks whose face is perpendicular to the minimum horizontal stress that are open, giving rise to a slower P wave velocity in that direction.

The presence of HTI or azimuthal anisotropy in the rocks manifests in the form of azimuthally varying velocity and therefore varying changes in amplitude, and if not corrected can lead to loss of frequency after stacking, poor fault resolution, and overall degradation of seismic reflections, amongst others. The azimuthally sorted seismic gathers can depict the presence of azimuthal anisotropy in the data.

Finally, in Figure 2d, we show the case where both VTI and HTI are present in the rocks, and which is referred to as *orthorhombic anisotropy*.

It is important to realize that the effects of anisotropy, in whatever way they manifest in the subsurface, be accounted for appropriately. As seismic data analysis offers a promising approach for hydrocarbon exploitation, it becomes mandatory to understand the implications of not correcting for anisotropy in seismic data, and then adopt workflows to ensure optimum imaging of seismic reflections (VTI/TTI), or determination of the presence of aligned fractures.

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