[GC]The Fabric, or Internal Structure, of Rocks – The Patterns of Anisotropy*

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General Statement

Geology is the correct starting point for any geophysical discussion in AAPG. This article starts with the rock, progresses to the wave and concludes with our increased understanding of the rock. Here you will gain a basic understanding of how anisotropy in P-P seismic reflection data can add to our understanding of the rocks, specifically the reservoir, at depth.

Rocks are composed of minerals and contain layers, porosity and pore fluids, and are influenced by a tri-axial stress field (for the most part), plus local structure - faults, fractures, folds and small variations in curvature. Four words provide the fundamental description of rocks: homogeneity, heterogeneity, isotropy and anisotropy.

"Homogeneity" means spatial invariance in a property laterally and/or vertically. For example, the P-wave velocity (V_P), the shear-wave velocity (V_S) and density – the three primary characteristics we seek to learn from seismic data – are spatially invariant laterally or vertically.

"Heterogeneity" means that there is a lateral or vertical change in V_P, V_S, and/or density: facies changes or the vertical stratigraphic column. The layers of sedimentary rocks are the primary heterogeneity that we map using reflections that arise at impedance (velocity times density) contrasts.

"Isotropy" means that, for a given volume of rock of interest, whatever measurement you wish to make shall yield to you the same value, no matter which direction in which it is measured.

"Anisotropy" means that, for this volume of rock, whatever the direction in the measurement is made shall determine its value. These four words usually exhibit scale-dependency. That is, the frequency used for the seismic measurement will determine your assessment of the rock. For the purposes of this article, I am speaking of the surface seismic reflection data, with frequencies of 5-100 Hertz (5-100 cycles per second).

Permeability and Velocity

Examples of anisotropic quantities are permeability and velocity. Engineers are familiar with the permeability (K) anisotropy of rocks: $K_{vertical}$ is not equal to $K_{horizontal}$; some reservoirs exhibit a K_{Hmax} which is not equal to K_{Hmin}. V_P and V_S are notorious for being anisotropic in the sedimentary layers that can contain hydrocarbon reservoirs.

"All anisotropy arises from ordered heterogeneity smaller than the wavelength." This sweeping statement from Don Winterstein's article in Geophysics, "Velocity anisotropy terminology for geophysicists," remains unrefuted. The wavelength is determined by the frequency and the velocity (frequency x wavelength = velocity). The ordered heterogeneities smaller than the wavelength can include shale clay platelets and finely layered rocks. Other ordered heterogeneities may be one set of vertical aligned fractures. The word "fracture" is very unspecific: it lumps together stress-aligned micro-fractures (arising from unequal horizontal stresses) whose apertures are too small to flow fluids, and macro-fractures that flow fluids. We would prefer to find (and document) a method that will empirically disentangle these two situations, even at the risk of arousing the ire of the theoreticians. If there are heterogeneities ("crack-like pores") smaller than the wavelength, but they are disordered, then we are back to seismic isotropy. True matrix porosity will look the same for all azimuths. The word "azimuth" in this article is the direction from source to receiver that the wave travels.

Rock Symmetry

In the world of anisotropy, there are four words or phrases that need to be known: transverse isotropy, orthorhombic, monoclinic and triclinic. These words indicate a certain symmetry (order in the heterogeneities) that we want to know about. The symmetry of the rock is imprinted upon the wave. By recording and displaying the symmetry of the wave, we deduce the symmetry of the rock. Although the more accurate statement is that the wave is influenced by the symmetry of the last layer through which the wave travels, geophysicists have various means to try to peer through the upper layers in order to see the reservoir conditions. We have to strip off the effect of the upper layers, in order to see the properties of the layer of interest (the reservoir). To "display the symmetry of the wave," I refer to inspecting interval travel times, amplitudes, frequencies, etc., as a function of azimuth and offset, from 0-180 (north to south) or from 0-360 (north to south to north), preferably the latter.

The principal order in the heterogeneities smaller than the wavelength is the layering of the rocks: we routinely expect to find a plane of isotropy in the bedding plane. If there is a plane of isotropy we have transverse isotropy (TI). Now we have to state the normal to the plane of isotropy. Transverse isotropy with a vertical axis, VTI, is the layer anisotropy (see Figure 1). Transverse isotropy with a tilted axis is TTI (dipping beds). VTI or TTI means that the P wave traveling parallel to the bedding plane will have the same (faster) velocity whether it travels north or east or south, etc. However, normal to the bedding plane, the P wave velocity will be slower. Figure 2 presents schematically the symmetry terms.

Transverse isotropy with a horizontal axis, HTI, is the symmetry of one set of vertical fractures: the P-wave traveling parallel to the fractures will travel faster, while the P-wave traveling normal to the fractures will travel slower. Evidence of azimuthal P-P travel times is visible in Figure 3a where the farther offsets show the travel time variation by source-receiver azimuth (a wobble, red arrow). The data are sorted first by offset group, then by azimuth within each offset group. The corrected travel times for orthorhombic processing are shown in Figure 3b. The red arrow indicates where the azimuthal travel time variation is greatly reduced.

This medium is also bi-refringent ("two waves") for the shear-wave: the vertically propagating shear wave with particle motion parallel to the fractures will travel faster; the vertically propagating shear wave with particle motion perpendicular to the fractures will travel slower. Shear-wave splitting occurs when the shear-wave with arbitrary polarization (particle motion skew to the fabric of the rock) enters the medium with one set of vertical aligned fractures: the one shear wave will become two shear waves.

Orthorhombic (ORT) is flat layers with one set of vertical aligned fractures; flat layers with two sets of orthogonal fractures is also allowed in the ORT symmetry. Note that you do not know whether I am referring to stress-aligned micro-cracks or macro-fractures that flow fluids, or some combination thereof. It turns out that across North America (and the rest of the world) about a 2 percent azimuthal variation in the P-wave V RMS is common (according to Ed Jenner, a senior geophysicist at NEOS). The word "azimuth" refers to the source-to-receiver direction (usually referenced to north when data is delivered to the client). We know that macro-fractures that flow fluids are rather rare, and not found everywhere all the time. Therefore, our seismic data is telling us that there is a background ubiquitous effect across continents that causes azimuthal variation in the P-wave velocities: it is likely the unequal horizontal stresses. When our migration (imaging) algorithms accurately specify the velocity field that changes with space (heterogeneity) and offset (layer anisotropy) and azimuth (unequal horizontal stress and/or vertical aligned fractures), then our images are clear and crisp.

ORT is the current standard symmetry for the industry … plus we have as "attribute" volumes the quantification of the velocity fields – and these we use in interpretation. Velocity is affected by lithology, porosity, pore fluids, horizontal stress (in the direction of source to receiver) and fracture sets. From laboratory studies, we know that stress in the direction of source to receiver has a proportional effect upon the P-wave velocity. The standard explanation for the laboratory observations is that increasing the stress in one direction will close the micro-cracks that are normal or near normal to the increased stress; this closure of the cracks normal to the increased stress will increase the P-wave velocity. Interval velocities (V_{INT}) average large volumes of rock, bounded by reflectors, and tend to change slowly spatially. The reflection amplitudes, however, are a spatially high-resolution dataset: they record the local contrast in impedance. The macro-fractures that flow fluids usually govern the azimuthal amplitude signatures: at least, this can be an initial hypothesis, to be tested against your own seismic data and calibration data. Since azimuthal V_{INT} and azimuthal amplitudes are arising from different volumes of rock, they need not agree. If they do agree, that is fine. When they do not agree, we note the heterogeneity between the two different rock volumes.

Anisotropy

So far I have explained that the wave acquires the symmetry of the rock: by examining azimuthal travel times and amplitudes, we document the symmetry of the wave and learn of the symmetry of the rock ("symmetry" is the fabric or order in the heterogeneities). I introduced the terms "homogeneous," "heterogeneous," "isotropic" and "anisotropic," schematically reviewed in Figure 4.

In the anisotropic category, TI (transverse isotropy) is used to indicate that a plane of isotropy exists. Its normal can be vertical (VTI, for the layer anisotropy) or horizontal (HTI, for the fracture or azimuthal anisotropy). Orthorhombic (ORT) is VTI + HTI, or flat layers plus one set of vertical fractures. Flat layers plus two sets of orthogonal vertical fractures can also give rise to ORT symmetry.

The words “orthorhombic,” “monoclinic” and “triclinic” are like a family: they are related because now we are talking about how many right angles are there among the three axes (or principal planes of the anisotropy). If there are three right angles, we have orthorhombic: flat layers plus one set of vertical fractures. If there are two right angles, we have monoclinic: for example, dipping layers plus one set of vertical aligned fractures or vertical faults; or flat layers plus one set of dipping fractures or dipping faults. If there are no right angles, we have triclinic: for example, dipping layers plus two different non-orthogonal sets of fractures (possibly the stress-aligned micro-fractures from the unequal horizontal stresses, and the dipping faults or macro-fractures that flow fluids), wherein all these planes are non-orthogonal to each other.

Geologists: which of these symmetries is likely present in the dataset your team is working?

Our industry state-of-the-art processing is 3-D P-P full azimuth full offset migration in the orthorhombic or tilted orthorhombic symmetry. To build the correct velocity model, the data can be 5-D interpolated into four, six or eight azimuth-sectors (more is better), and the TTI model is used to build the velocity field for that azimuth. Then, an algorithm takes the azimuth-dependent velocities and builds the ORT velocity field from the observed travel times. There are other methods for preserving azimuth and offset during the migration step, but lack of space precludes me from digressing to there. If you have not reprocessed your data within the last five years, it is now time to reprocess to obtain the uplift, new gathers and additional attribute volumes.

360 Degrees

Geophysicists map the travel times (structure, V_{INT}) and the amplitudes – the wave acquires the symmetry of the medium through which it travels. If the rocks contain the symmetry that the processing algorithm requires (i.e. expects), then all is fine. If the rocks are more complicated than the processing algorithm’s expectation, poorer images can result.

Figure 3 (c and d) compare the images obtained with two different assumptions about the symmetry of the rocks. This area of offshore Vietnam is fairly complex structure, and so the ORT assumptions are being “pushed” (that is, I would not argue that these rocks are ORT). Dipping reflectors and dipping faults are clearly visible. Perhaps this explains why the deeper reflectors on the gather (Figure 3b) appear to have some remnant azimuthal time wobble present. Note especially the time wobble on the near offsets of the deep reflectors. Possibly, further subsequent processing did remove those azimuthal travel time variations.

Risking arguments, I assert that for monoclinic and triclinic symmetries, we would do well to process P-P reflection data 0-360, and not 0-180. How can we know what is going on in the field data unless we look at it? My whole career has been one long series of arguments, starting in 1980 at Amoco, when I was asked to process two SH-SH reflection lines that tied at Devil’s Elbow, Pennsylvania. These two SH-SH reflection lines happened to lie in the principal planes of the anisotropy and exhibited a time-variant (dynamic) mis-tie at the tie point. This was the first published evidence of shear-wave splitting in oil company reflection seismic data. This field dataset sparked Rusty Alford’s (of Amoco) interest in split shear waves, so he went to Dilley, Texas, and acquired 2-D four-component shear wave reflection profiles (SH and SV sources recorded by the inline and crossline horizontal geophones). The shear wave splitting contained in Alford's data were published at the 1986 Society of Exploration Geophysicists' Annual Meeting "Anisotropy" session; Alford was subsequently presented with the Kaufmann Gold Medal for his important contribution to the industry.

Rocks that are folded or curved can exhibit various regions of aligned fractures, curved layers being held in extension or in compression. A neutral plane can separate layers held in extension from layers held in compression. We often observe the azimuth of $V_{INTfast}$ to change by 90 degrees when comparing one layer held in extension to a (lower) layer held in compression, for example, as in a mild anticline. For a mild syncline, the upper layer is held in compression, but the lower layer is held in extension. In 1994, Bruno and Winterstein published an important study into the relationship of stress variations within folds (using shear-wave data and modeling).

Conclusion

The internal structure of the rock, its fabric, can be studied by examining the anisotropy exhibited by the layer. Geophysicists routinely measure the interval velocity azimuthal anisotropy to compare to support data showing in situ stress (e.g. borehole breakout) and macro-fractures; and the azimuthal amplitude anisotropy is compared to support data for macro-fractures and *in situ* stress. To understand the AVO gradient change with azimuth (the industry standard), the azimuthal variation of the far offset amplitudes is quantified and mapped; as well as the azimuthal variation of the near offset amplitudes (see Lynn, SEG Expanded Abstracts, 2014, 2015, 2016). HTI amplitude modeling, through the CREWES website TI Explorer programs, is also employed to document "what we expect." Azimuth-dependent prestack elastic inversions are also important for obtaining the azimuthal variation in P-impedance, S-impedance and density (third term). All these measurements are tied to the local calibration data to assure management that "our interpretation is consistent with all the observations."

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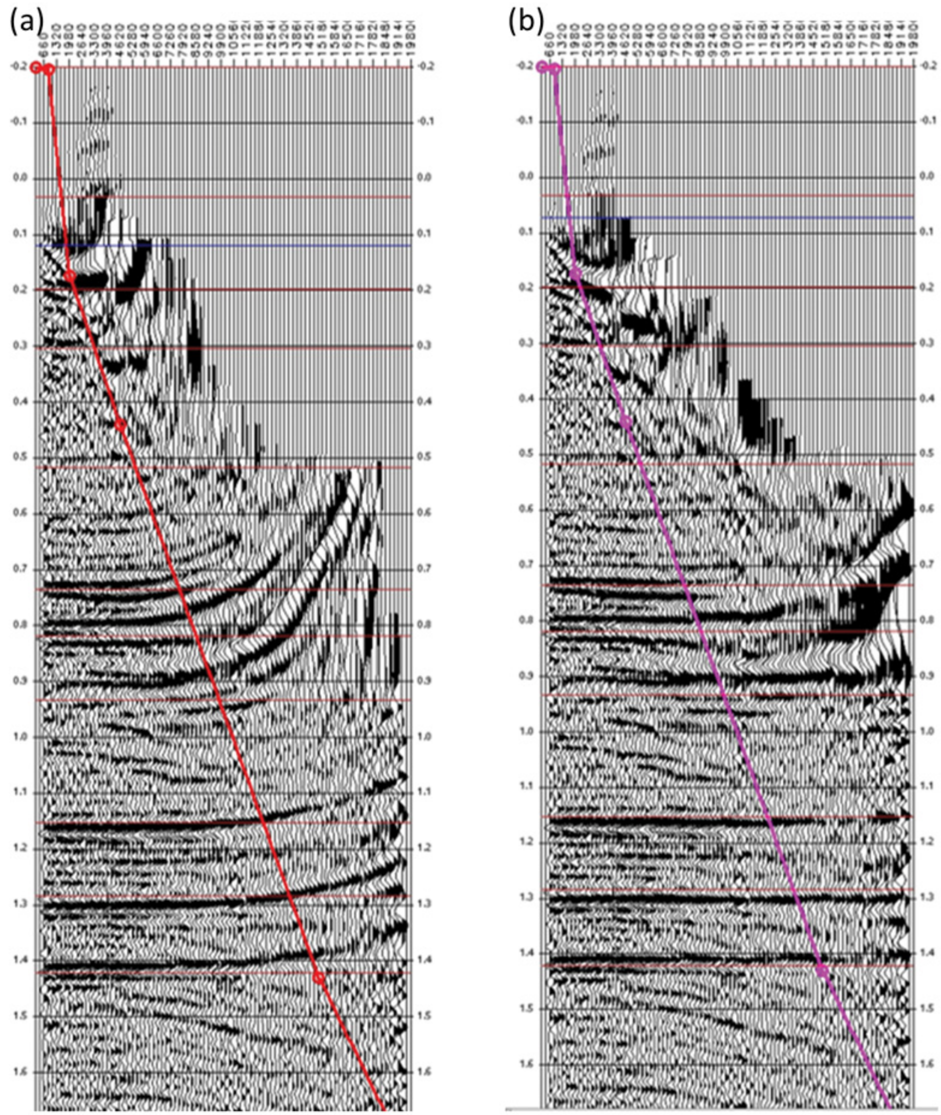

Figure 1. P-P reflection seismic data, one gather with traces ranging in source-receiver offset from 660 feet to 19,800 feet. These two gathers illustrate the effect of VTI (layer anisotropy) on P-P data. (Left) The reflectors are fairly flat on the near offsets. The curve up is due to the faster velocity encountered on the greater offsets. The red line is a possible mute function. (Right) The same data after the eta (nonhyperbolic moveout) correction. Now the reflectors are flat in time across the gather, ready for stack. The pink line is the mute function: the offsets greater than the mute are zeroed prior to stack. Stacking the data now will increase the S/N because now all the events are aligned and in phase. (Figure courtesy of TGS)

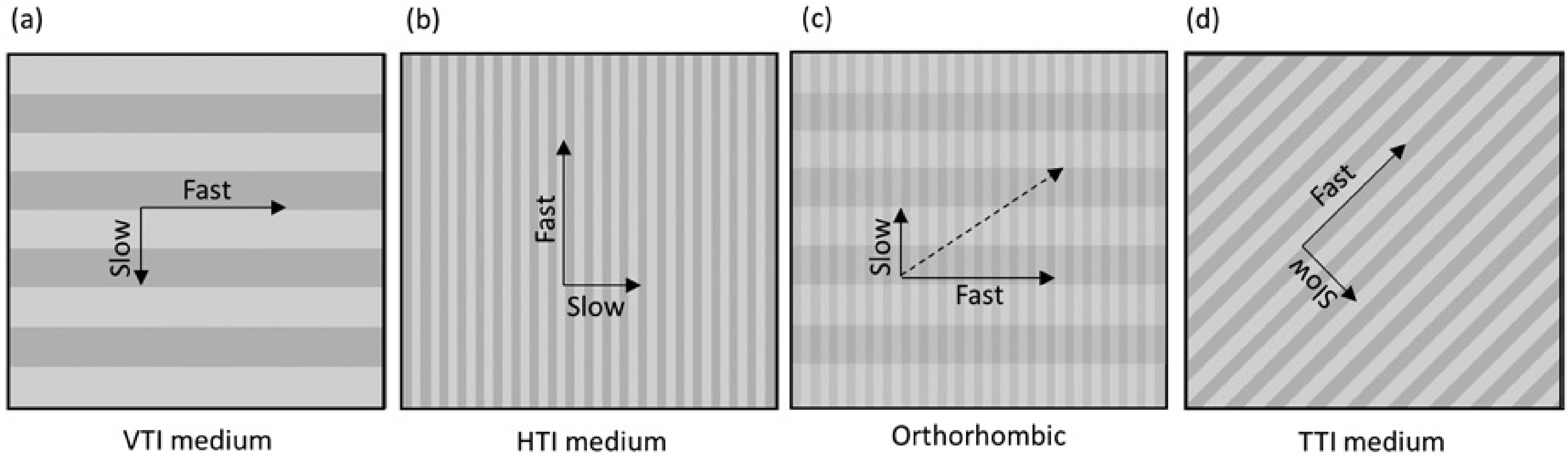

Figure 2. VTI: sedimentary layers. HTI: one set of vertical aligned fractures. Orthorhombic: VTI + HTI. TTI: tilted TI, dipping sedimentary layers. The length of the black arrow is proportional to velocity (measured in direction that arrow points). The 3-D picture of the orthorhombic black arrows has the dashed arrow being into the plane of paper and parallel to the vertical aligned fractures. (Figure courtesy of Satinder Chopra)

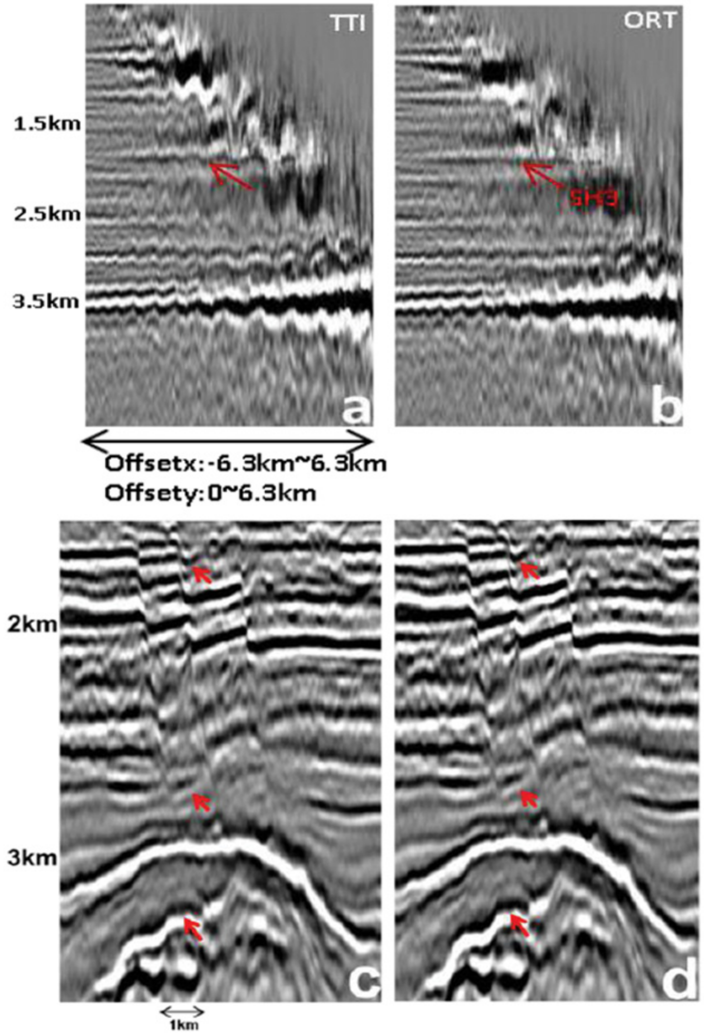

Figure 3. P-P reflection data from an ocean bottom survey, offshore Vietnam. (a) An azimuth-sectored TTI common image gather after four iterations of tomographic update from water bottom to top of basement (anticline reflector at ~3-kilometer depth). Data is sorted as a “snail” gather, meaning there are a suite of offset bands within which the azimuths go from North to South. The TTI prestack depth migration has taken care of the layer anisotropy, but has left in the azimuthal traveltime wobble (see red arrow). (b) Initial ORT common image gather. The ORT velocity field has specified the VTI and HTI effect sufficiently to flatten the event (red arrow). (c) Azimuth-limited TTI stack section. (d) Initial ORT stack section. The red arrows point to locations where the ORT prestack depth migration has improved the image. Because the azimuthal traveltimes are corrected, the stack can use all azimuths and all offsets, for superior S/N. Moreover, we now have the ORT migration velocity field to use in interpretation: a very important step. (Adapted from Jiao, et al., 2017)

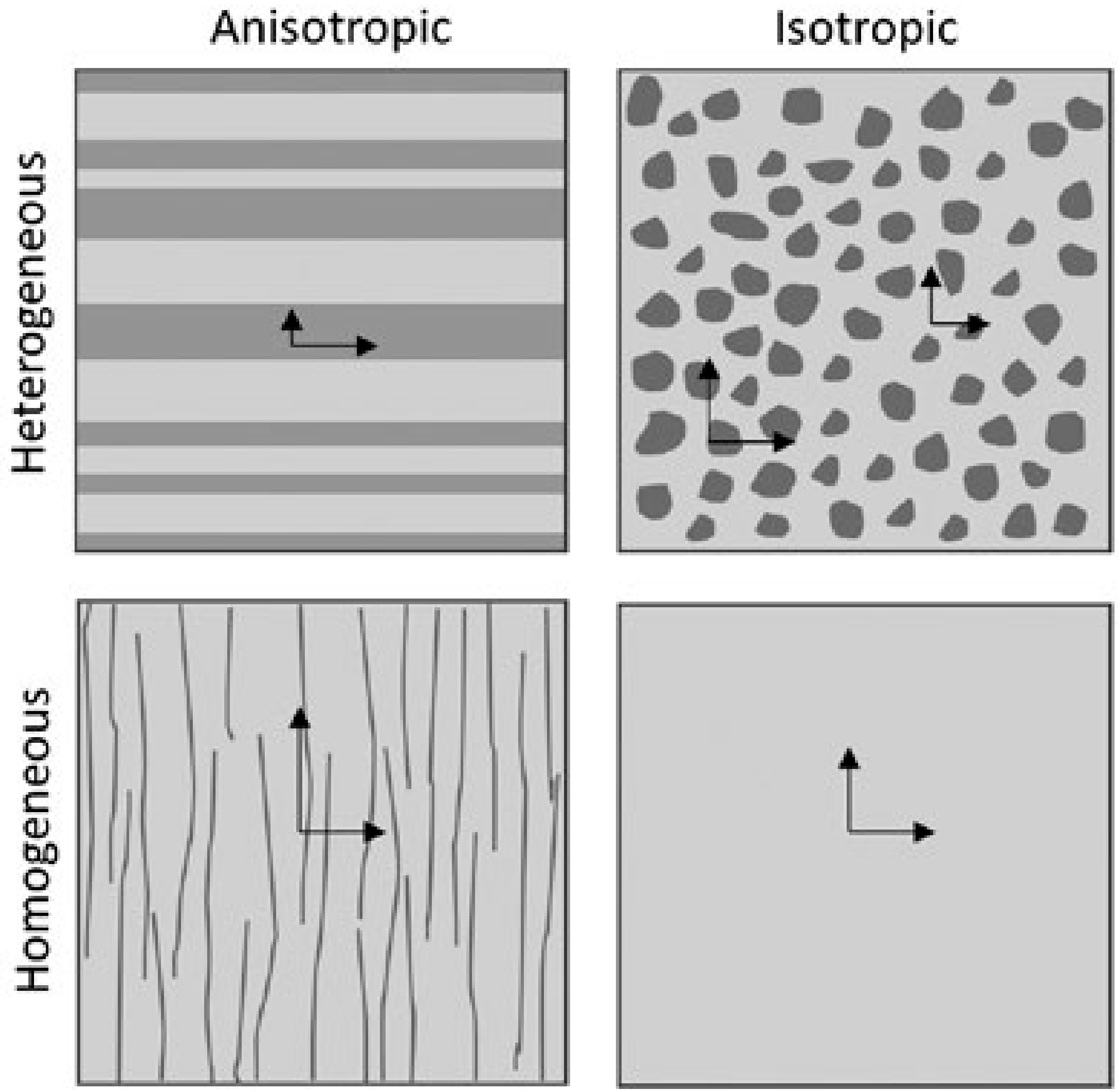

Figure 4. Sketches of possible scenarios to illustrate the four terms. Length of black arrow is proportional to velocity (as measured in direction arrow is pointing). Figure courtesy of Satinder Chopra.