GC Determining Brittleness from Seismic Data*

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General Statement

The key elements for shale resource evaluation are the mineral content – such as clay, quartz and calcite – the total organic carbon (TOC) content, the brittleness and some mechanical properties of the shale rocks. Geomechanical studies are necessary both for understanding wellbore environment stability and also interpreting well log data, by estimating the mechanical properties of the subsurface.

Simply stated, an accurate geomechanical model needs to be conceived, and its main features are the three principal elements – stresses, pore pressure and the rock strength. Availability of these parameters define a good geomechanical model, which help with the evaluation of wellbore stability, fracture permeability, drilling direction and others. Highly brittle shale formations fracture better, and thus provide more fracture pathways for release of the hydrocarbons. The shale's mineral content can be determined from the XRD analysis, or estimated from the wireline well log curves. Similarly, brittleness and TOC can be estimated from the well log data – but this information is only available at the location of the wells.

In this article we focus on determination of brittleness of shale formations from seismic data – and demonstrate that brittleness is a relative term that has no standardization and needs to be carefully calibrated with the relevant data before it is used for interpretation. Before we go ahead with that description, some common definitions of terms and elastic constants used in the discussion on brittleness are discussed first.

Brittleness Defined

When a slab of rock is acted upon by a force, it is expected to undergo a change in its dimensions. For simplicity, let us consider the change along the length of the slab. The force acting on a unit area of the rock is referred to as stress, and is commonly measured in Pascals (Pa) or pounds per square inch (psi). The resultant change in length of the rock or the rock's deformation in response to the stress is measured as the change in length per unit length, and is called strain. Being a ratio of two lengths, strain has no units.

Strain may be of three types, depending upon the change produced in the rock on the application of stress:

1) Longitudinal strain is the change in length per unit length.

2) Volumetric strain is the change in volume per unit volume.

3) Shearing strain is the angle through which a face of the rock sample perpendicular to the fixed face is turned.

As a result of the tectonic activities that Earth experiences, subsurface rocks undergo two types of stresses – the stretching or extensional types of stresses, (or tensile stresses, implying the rock is under tension), and the compressive stresses. The strains corresponding to these two types of stresses are referred to as tensile and compressive strains respectively.

When the strain produced in a slab of rock is plotted against the applied stress, the graph shown is a straight line, implying stress is proportional to strain – a result known as Hooke's Law. The gradient of the straight line is referred to as Young's Modulus, usually denoted as E. Young's Modulus is a constant for a given material and is a measure of its stiffness. It is measured in Pascals (Pa) or pounds per square inch (psi). For the rocks that we commonly deal with, E turns out to be a large number, and thus larger units such as Mega Pascals (MPa) or Mega psi are commonly used.

Similarly, depending on the two other types of strain, we talk of two other moduli of elasticity – namely bulk modulus (κ), which corresponds to volume strain and is a measure of the rock's incompressibility, and shear modulus (μ), which corresponds to shearing strain and is a measure of the rock's rigidity. Besides these, there is another elastic constant, (λ), that is commonly employed in rock physics and is related to the bulk modulus. For this reason it is considered a proxy for incompressibility of the rock samples. Both λ and μ are also known as Lame's constants, named after the French mathematician, Gabriel Lamé.

When a slab or rock is compressed in one direction, it tends to expand in the other two directions, perpendicular to the direction of compression. The ratio of the fractional expansion to the fractional compression of a rock is referred to as Poisson's Ratio (ν) – it is a measure of the rock's strength, and its values for most rock types range from 0 to 0.5. Thus there are different elastic constants (E, ν, κ, μ, λ) that are used for characterizing reservoirs. Knowledge of any two of them allows the computation of the others. The values of these constants are usually determined in the laboratory by making two distinct types of measurements on rock samples.

The first types of measurements are those wherein the rock samples are loaded with known stress magnitudes and the resulting strain amplitudes are measured. A typical application of stress on a core sample of the subsurface rock – and studying how it fails – is called the uniaxial compressive test, where the two other stresses are zero (Figure 1a). Such a test yields the rock's unconfined compressive strength and can easily give away along the planes of weakness in the core sample.

A more preferred test is the triaxial compressive test (Figure 1b), wherein confining stress is applied on the core sample, and then the axial stress is applied until it fails. While performing such tests, the axial strain is noted as a function of axial stress and the two are then plotted. Figure 2 shows such a tensile stress-strain curve.

As mentioned above, Hooke's Law relates the applied stress to the resultant strain and postulates that this relationship is linear. The slope of the linear or straight-line stress-strain curve yields the Young's Modulus. The temporary change in shape of the rock samples under applied stress such that it regains its original position once the stress is removed, is referred to as elastic deformation. However, as the applied stress is continuously increased, the elastic limit of the rock sample is crossed, so that the straight line deviates into a curved segment exhibiting plastic deformation, i.e. rocks undergo permanent deformation when the applied stress is removed. The curved segment on the stress-strain plot shows that the rock sample does not immediately regain its original position and needs more time. This is referred to as viscoelastic behavior of the rock sample. If the rock sample is subjected to more stress loading, it could reach its failure limit, when the rock sample could get ruptured.

Depending on their characteristics, rocks are normally classified as either brittle or ductile. These two can be differentiated based on the amount of plastic deformation that the rock undergoes before fracture occurs. Figure 2 illustrates that extensive plastic deformation occurs in the ductile rocks prior to fracture, while brittle rocks show little or no plastic deformation before fracture. As the area under the curves is a measure of the absorbed energy, it can be stated that ductile rocks absorb very much energy before getting fractured while brittle rocks absorb less energy prior to being fractured. Young's Modulus or Poisson's Ratio calculated from such stress-strain or deformational measurements are referred to as static moduli.

The second type of measurements carried out for the laboratory determination of elastic constants are where velocity is used for their calculation. For example, ultrasonic waves are made to travel through a known length of a rock sample, and the corresponding travel time is determined from the first arrival of both compressional and shear waves. The Young's Modulus and Poisson's Ratio computed from these velocities and density are referred to as dynamic moduli. Such dynamic computations could be carried out from sonic log data, as well as seismic surveys – and the only difference between the velocities would be their measurements at different frequencies, namely kiloHertz for sonic logs and close to hundred Hertz or so for seismic data.

Static and Dynamic Moduli

The static and dynamic moduli of rocks usually differ from one another – and usually the dynamic Young's Modulus is greater that the static Young's Modulus. In a similar vein, the static Poisson's Ratio is greater than the dynamic Poisson's Ratio. While the physical causes for the difference between the static and dynamic moduli are not clear, it is believed that the discrepancy is due to the fact that in their analysis, rocks do not behave as elastic, homogeneous and isotropic as they are assumed to be.

Rocks usually behave as viscoelastic, due to many different processes – including the inter-granular cracks arising due to the granular nature of the sedimentary rocks. Such inelastic mechanisms respond differently to the static and the dynamic strain amplitudes and frequency, which is dependent on the properties of the rocks. One suggestion for this discrepancy is the large difference in the static strain magnitudes, which could reach 10^{-2}, and the strain magnitudes for dynamic wave measurements, where they may be of the order of 10^{-7}. Thus the difference between the strain magnitudes could be between four to six orders of magnitude. To illustrate this difference, we pick up the measured values of static and dynamic Young's Modulus and Poisson's Ratio carried out on the Baxter Shale (from the 2008 SPE article 115736, by Higgins et al.).

The Upper Cretaceous Baxter Shale is located in the Vermillion Basin of northwestern Colorado and adjoining Wyoming. Dry gas production has been established from more than two dozen wells in the Baxter, with over-pressuring seen in them. The silt-rich Baxter has vitrinite values approaching 2 percent, porosities in the range of 2-6 percent, TOC in the range of 1-3 percent and matrix permeabilities of 100 to 1,500 nanoDarcies.

Triaxial core samples were conducted on 20 samples drawn from 150 feet of the 2,000 feet of the Baxter Shale that represents the over-pressured portion. The samples were subjected to *in situ* conditions of the confining stress, and the measurements were made in the vertical and horizontal directions such that the stiffness constants in the stiffness tensor could be determined and allow accounting for transverse isotropy in the shale. It was found that the static and dynamic Young's Modulus values measured in the horizontal direction were significantly higher than the Young's Modulus values measured in the vertical direction. The measured static and dynamic Poisson's Ratio values in the vertical direction are slightly larger than the Poisson's Ratio values in the horizontal direction.

A comparison of the plotted static and dynamic Young's Modulus and Poisson's Ratio values are shown in Figure 3a and 3b. A well-defined relationship between the static and dynamic Young's Modulus is noticed – but not with Poisson's Ratio. Such variations, when accounted for, can appropriately characterize the inherent stress-strain relationship in the shale. In geomechanical studies, while studying the influence of *in situ* stress applications on breakouts, enhanced pore pressure or on the wellbore stability, static moduli are used in the calculations. It therefore becomes mandatory to calibrate the dynamic moduli (which are derived from seismic data) to the static moduli (derived from laboratory measurements), before they are used for geomechanical applications.

Methods for Brittleness Determination

Highly brittle shale formations are more prone to stimulated fractures – and they prove to be more productive in terms of release of hydrocarbons. These fractures also propagate in the direction of the minimum stress. In the shallow zone, as the minimum stress is the overburden stress, the stimulated fractures will be horizontal. In the deeper zones the minimum stress direction is horizontal, and thus the stimulated fractures are vertical. Quartz and calcite are brittle minerals, while clay is ductile. Thus higher content of the former two makes the shale more brittle, and more clay content makes it ductile. XRD analysis of shale samples may not be carried out commonly, but if available is useful. Their estimation from well data is also done by interpretation of the log curves. As the presence of TOC enhances the resistivity and reduces the velocity, a combination of these two log curves is usually used for its estimation. It is also determined by geochemical analysis of rock samples. As stated, its estimation from seismic data is desirable.

Given the mineral content (volume of mineral) of the shale sample, a simple way to estimate brittleness would be to determine the fraction (quartz + calcite) / (quartz + calcite + clay). This fraction is termed as brittleness index. If dolomite also happens to be present, then it should also be added to both the numerator and denominator of the above fraction. Another way to determine brittleness index for a shale sample is to make use of the elastic constants. One such proposed method makes use of the Young's Modulus (E) and Poisson's Ratio (ν). For brittle rocks, high values of Young's Modulus and low Poisson's Ratio are desirable.

Using these constants, the brittleness index can be expressed in a couple of ways:

1) One is to simply compute the fraction E/ν, which should have high values for brittle rocks.

2) A variation of this method could be the ratio $E\rho/\nu$. This ratio is especially useful when seismic data is being used for determination of E, which would require the density data. It is usually difficult to determine density from seismic data. Instead, $E\rho$ can be determined which only requires P- and S-impedance, easily derived by impedance inversion of seismic data.

3) Yet another way is to compute the average of the brittle Young's Modulus component and the brittle Poisson's Ratio component. That is $(E_B + \nu_B)/2$, where $E_B = 100(E-E_{min})/(E_{max}-E_{min})$ and $\nu_B = 100(\nu-\nu_{max})/(\nu_{min}-\nu_{max})$

Based on the observation that fracturable zones exhibit low values of $\lambda\rho$ and moderate values of $\mu\rho$, another estimation for brittleness index has been suggested and is given as $(\lambda+2\mu)/\lambda$. We discuss the comparative performance of these different methods first on well log data from the Duvernay Formation in Alberta, Canada.

Example

The Upper Devonian Duvernay Formation is situated within the West Shale Basin in west-central Alberta. The main Duvernay interval is the shale section that shows high values on gamma ray log curves. A thin zone below the Duvernay interval has a high composition of organic-rich lime-mudstone, and is called the Duvernay carbonate zone – it overlies the Middle to Upper Devonian Swan Hills Formation, consisting of a broad carbonate platform overlain with large reefs. The main Duvernay interval spans the "dry" gas, "wet" gas, and the "oil" windows, but at present more interest is focused on the "wet" gas window, where liquid-rich gas is being produced from horizontal wells with multi-stage fracture completions.

In Figure 4 a crossplot is shown between E and ν for a zone that encompasses all three zones mentioned above. Separate clusters of points are seen on the crossplot and when enclosed with polygons and projected back on the log curves, these points highlight the individual zones as marked. The cluster of points from the Duvernay zone exhibit low ν and moderate to high values of E, and thus should be exhibiting higher brittleness. In Figure 5, log curves from a well are shown in different tracks (a) to (i). In track (a), the sonic and resistivity curves are shown overlaid, and a crossover shaded in orange color in the Duvernay interval is seen. This probably could be the zone associated with high TOC as per Passey's approach. The Poisson's Ratio (ν) and Young's Modulus (E) curves are shown in tracks (b), and again crossover of curves are seen in the Duvernay interval (blue arrow) as well as Duvernay carbonate zone (green arrow) and Swan Hills interval (red arrow).

We will focus on the Duvernay interval here, which is the zone of our interest. Brittleness index curves (E/ν) and $(E_B + \nu_B)/2$ are shown overlaid in track (c). Notice these curves are similar in that they follow each other and small deviations are seen in the Duvernay interval. Similarly, again brittleness index curves (E/ν) and ($E\varrho/\nu$) are shown in track (d) with very small deviations seen in the Duvernay interval. Brittleness curves $(\lambda+2\mu)/\lambda$ and $(E_B + \nu_B)/2$ are shown in track (e), and these are found to be different. To understand the reason for this difference, we compute the E_B and ν_B components separately and compare them with E and ν curves as shown in tracks (f) and (g). We notice that while the E_B curve appears to be a normalized version of the E curve, the ν and ν_B curves are a reflection of each other. This latter observation also is seen when we overlay the ν and $(\lambda+2\mu)/\lambda$ brittleness index curves (track h). Finally the overlay of ν_B and $(\lambda+2\mu)/\lambda$ brittleness index curves as shown in track (i) and they look very similar. When the different brittleness indicators discussed above are computed from the seismic data using simultaneous or joint inversion (for more details on simultaneous inversion see Search and Discovery Article # 41664), they also are found to exhibit differences as we notice on the log curves in Figure 5.

In Figure 6 we show equivalent horizon slice displays within the Duvernay interval (averaged over a 10 ms window) for Poisson's Ratio (ν) (Figure 6a), $(\lambda+2\mu)/\lambda$ brittleness index (Figure 6b), and $(E\varrho/\nu)$ brittleness index (Figure 6d). We notice the Poisson's Ratio display shows low values while the $(\lambda+2\mu)/\lambda$ brittleness index displays shows high values, within the areas marked with dashed polygons. The equivalent Poisson's Ratio displayed in Figure 6c in reverse color bar looks very similar to the brittleness index display in Figure 6b – an observation made on the two well curves in track (h) of Figure 5. Brittleness index curves $(\lambda+2\mu)/\lambda$ and $(E\varrho/\nu)$ show similar distribution within the dashed polygon on the left, but is different within the dashed polygon to the right, as well as to the left of the display indicated with the blue arrows. Such difference seen on the different brittleness index curves on these attributes extracted from seismic data are likely to cause confusion while interpreting them.

Delving closely into the determination of the brittleness index attributes in terms of elastic moduli, one finds that the upper and the lower limits chosen for, say E and ν are arbitrary. Thus their interpretation will be done only in a relative sense, and could be seen as a drawback. Even otherwise, considering brittleness as a mechanical property of rocks, there are no standardized levels above or below which the rocks could be considered brittle or ductile. Instead of just carrying out such a relative or qualitative interpretation of brittleness, more effort could be devoted to understand the rocks physics of the intervals of interest, which could yield an optimal range of E and ν to be considered in our analysis.

For accurate quantification of brittleness, theoretical rock physics templates (including mineralogy, etc.) for the broad intervals of interest can be generated, such that the trends for the lithologies of interest can be studied. With the use of the available well log data, the validity of such templates can be verified for the area of operation. Finally such templates can be used to interpret the brittleness index displays generated simultaneous inversion (for more details on simultaneous inversion, refer again to Search and Discovery Article # 41664).

In Figure 7, we show such a crossplot template between Poisson's Ratio and Young's Modulus, where lines pertaining to constant bulk modulus are drawn. Rocks with higher quartz content will generally exhibit lower Poisson's Ratio and higher Young's Modulus. With increase in porosity, the bulk modulus decreases, and so does Young's Modulus. Similarly, more clayey rocks will have higher Poisson's Ratio and low Young's Modulus.

Conclusion

The parameters that we should consider for the possibility of fractures in a shale rock are *in situ* stress, Poisson's Ratio and Young's Modulus. By constructing such crossplots for the parameters in the area of interest, it is convenient to determine the range of values that should be expected for the different elastic constants. This information could then be used during interpretation of those elastic constants derived from seismic data. Such exercises prove useful for carrying out quantitative interpretation of seismic data.

Acknowledgement

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Reference Cited

Higgins, Shannon M., Scott A. Goodwin, Adam Donald, Tom R. Bratton, and George W. Tracy, 2008, Anisotropic stress models improve completion design in the Baxter Shale: SPE 115736-MS.

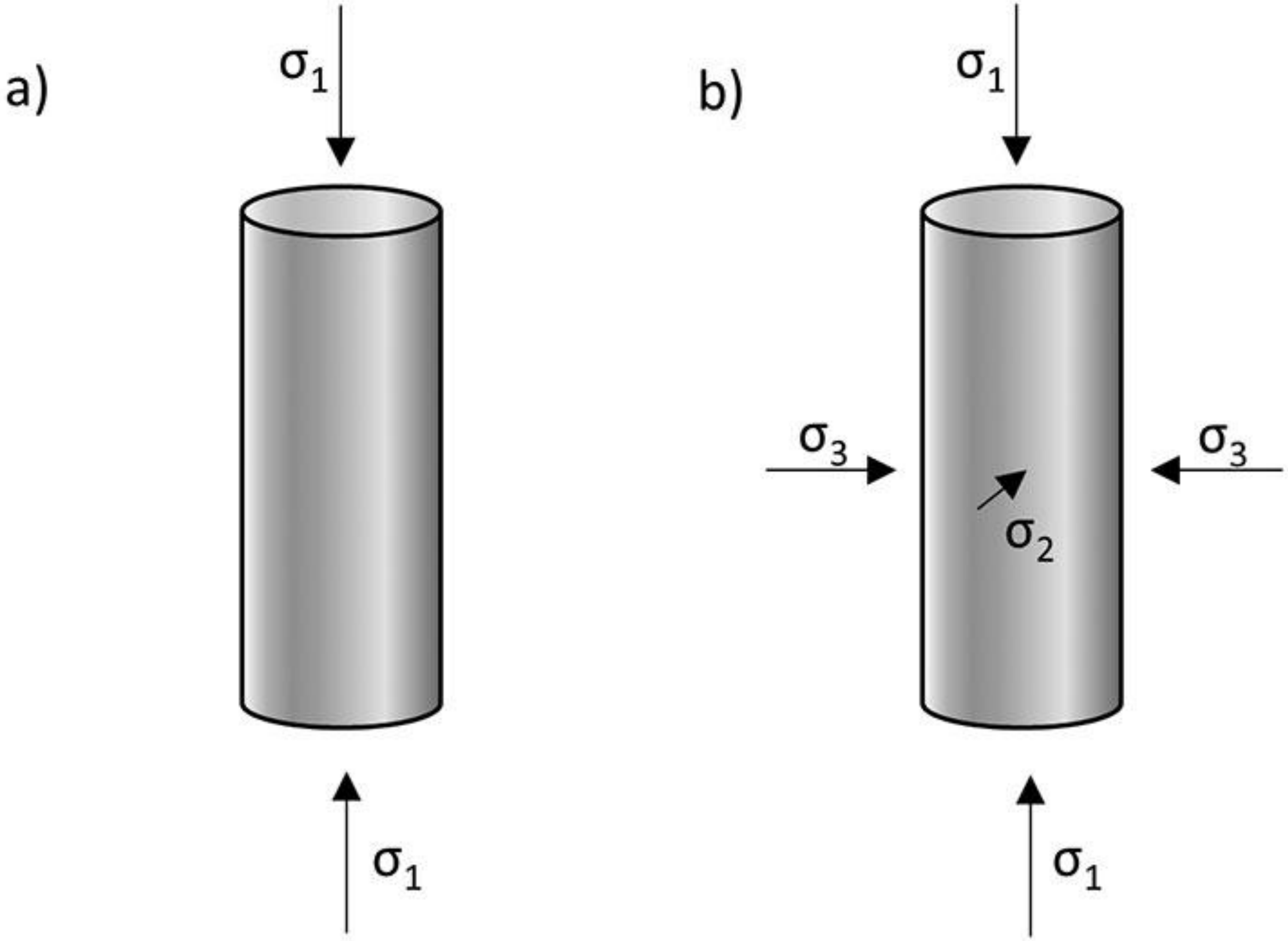

Figure 1. Schematic showing application of (a) uniaxial, and (b) triaxial on rock samples.

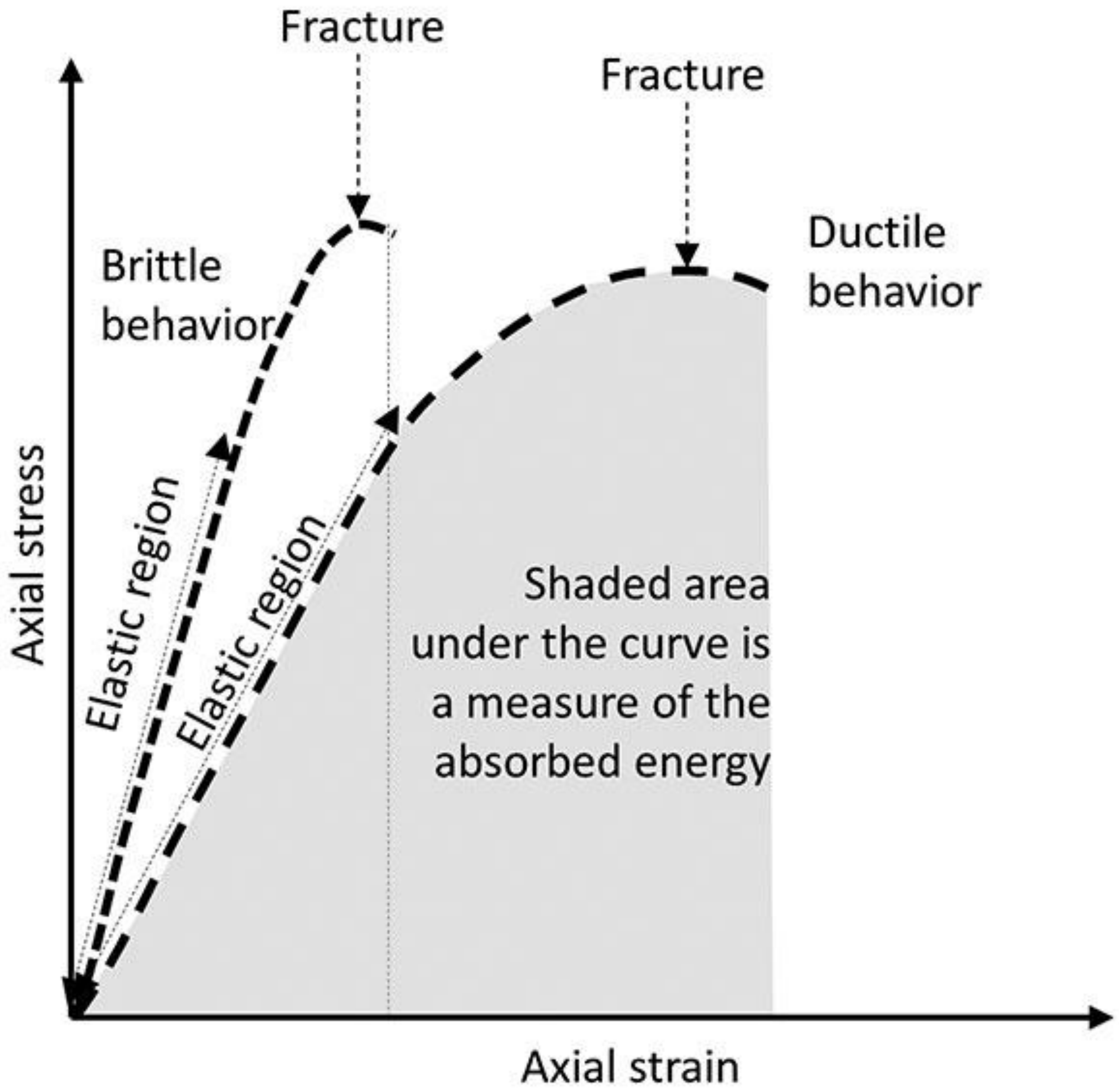

Figure 2. Brittle versus ductile behavior of rock samples as seen on a stress-strain graph.

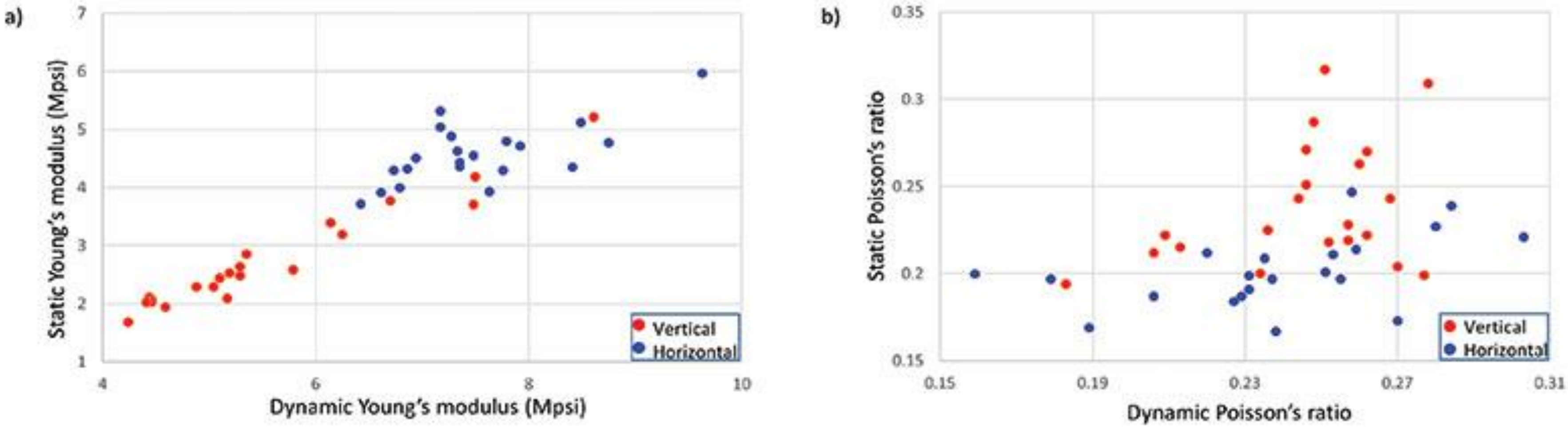

Figure 3. (a) Static Young's Modulus (YM) values plotted against dynamic YM values. (b) Static Poisson's Ratio (PR) values plotted against dynamic PR values. The values were derived from vertical and horizontal measurements on Baxter Shale core samples and reported in SPE 115736 by Higgins et al. (2008). We notice that the horizontal static and dynamic YM are greater than the YM values in the vertical direction. The static and dynamic Poisson's Ratio (PR) measure in the horizontal direction are lower than the PR values measured in the vertical direction. Also, there is a well-defined relationship between the static and dynamic YM values, but not so between the static and dynamic PR values.

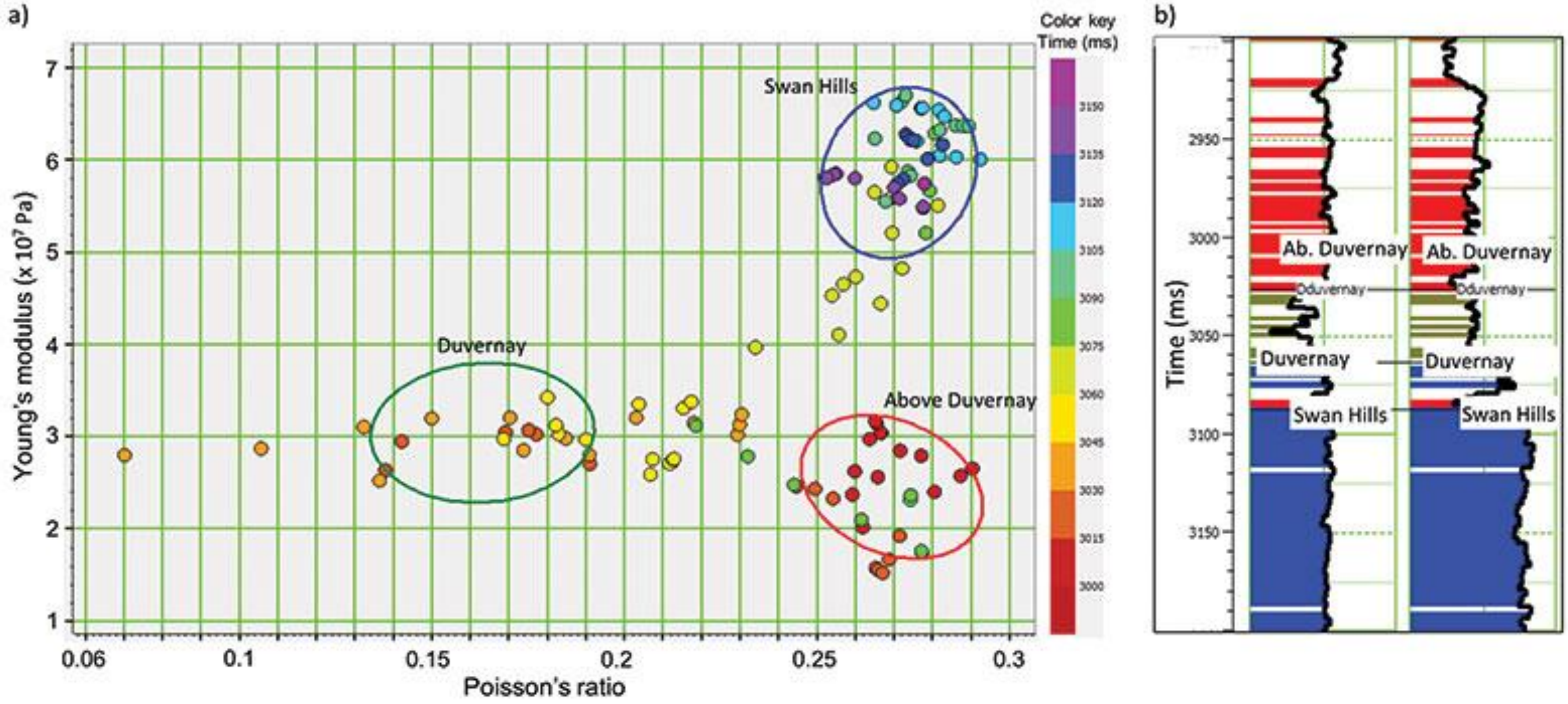

Figure 4. (a) Crossplot between Poisson's Ratio and Young's Modulus attributes for zone selected to cover the Duvernay, Above Duvernay and Swan Hills intervals on the log curves. Separate clusters of points are seen on the crossplot. Three clusters are enclosed with polygons and the enclosed points are projected back on to the log curves as shown in (b). The polygons highlight the zones as marked on the crossplot.

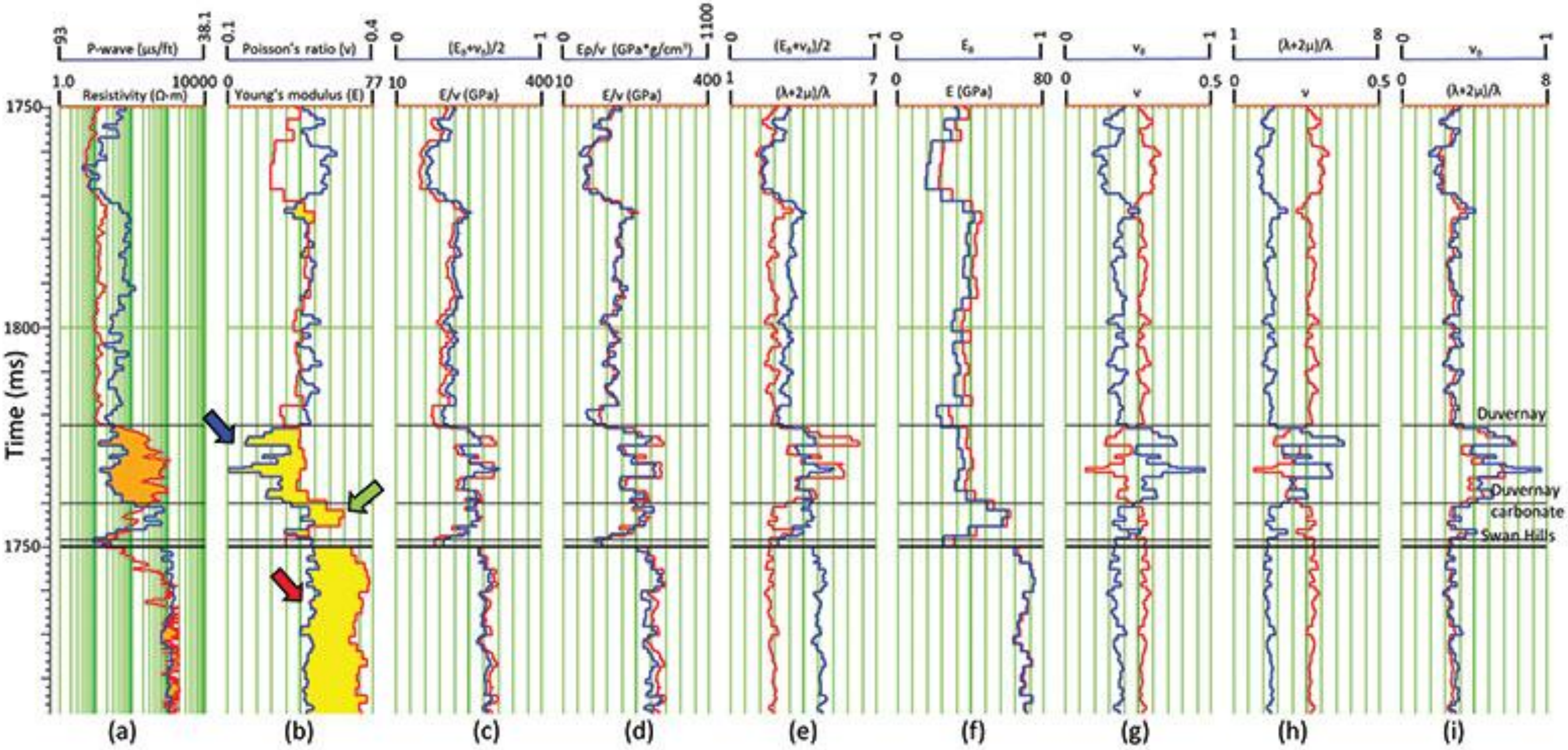

Figure 5. Log curves from a well in mid-central Alberta showing the Duvernay interval, overlaying Duvernay carbonate and Swan Hills formations. The highlighted orange zone is the crossover between the sonic and the resistivity and could be associated with high carbon content (track a). The crossover between the Poisson's Ratio and Young's Modulus curves is the highlighted yellow zone in track b. Besides the Duvernay, the Duvernay carbonate, which has a high content of calcite and the Swan Hills zones also are highlighted yellow, which is expected. Other brittleness index attributes have been plotted and the text may be referred to their interpretation.

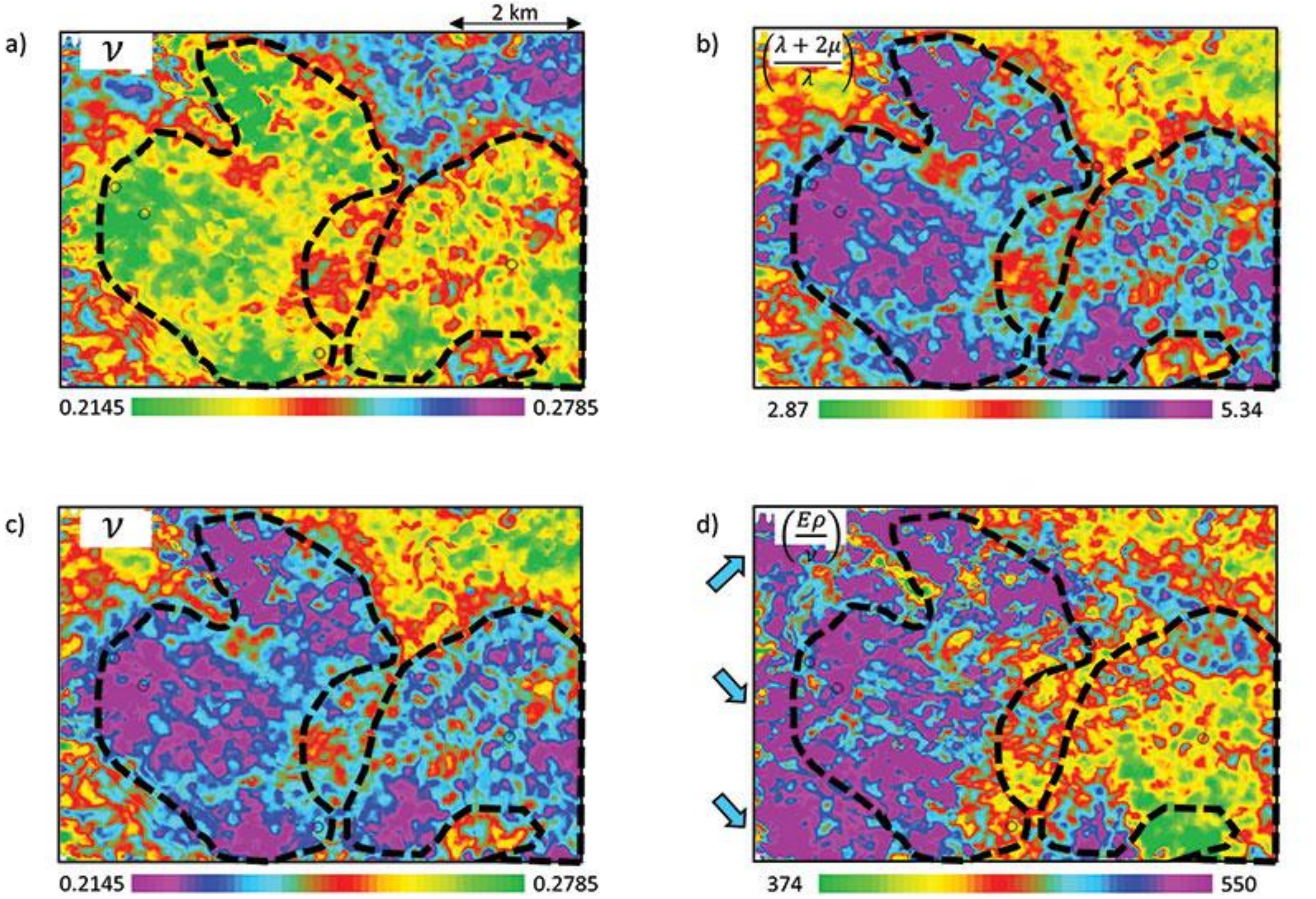

Figure 6. Horizon slices from (a) Poisson's Ratio, (b) brittleness index, (c) the same display as in (a) but with the color bar reversed, and (d) brittleness index. The displays depict the average in a 10 ms interval within the Duvernay zone. Apparently, the displays in (b) and (c) look very similar.

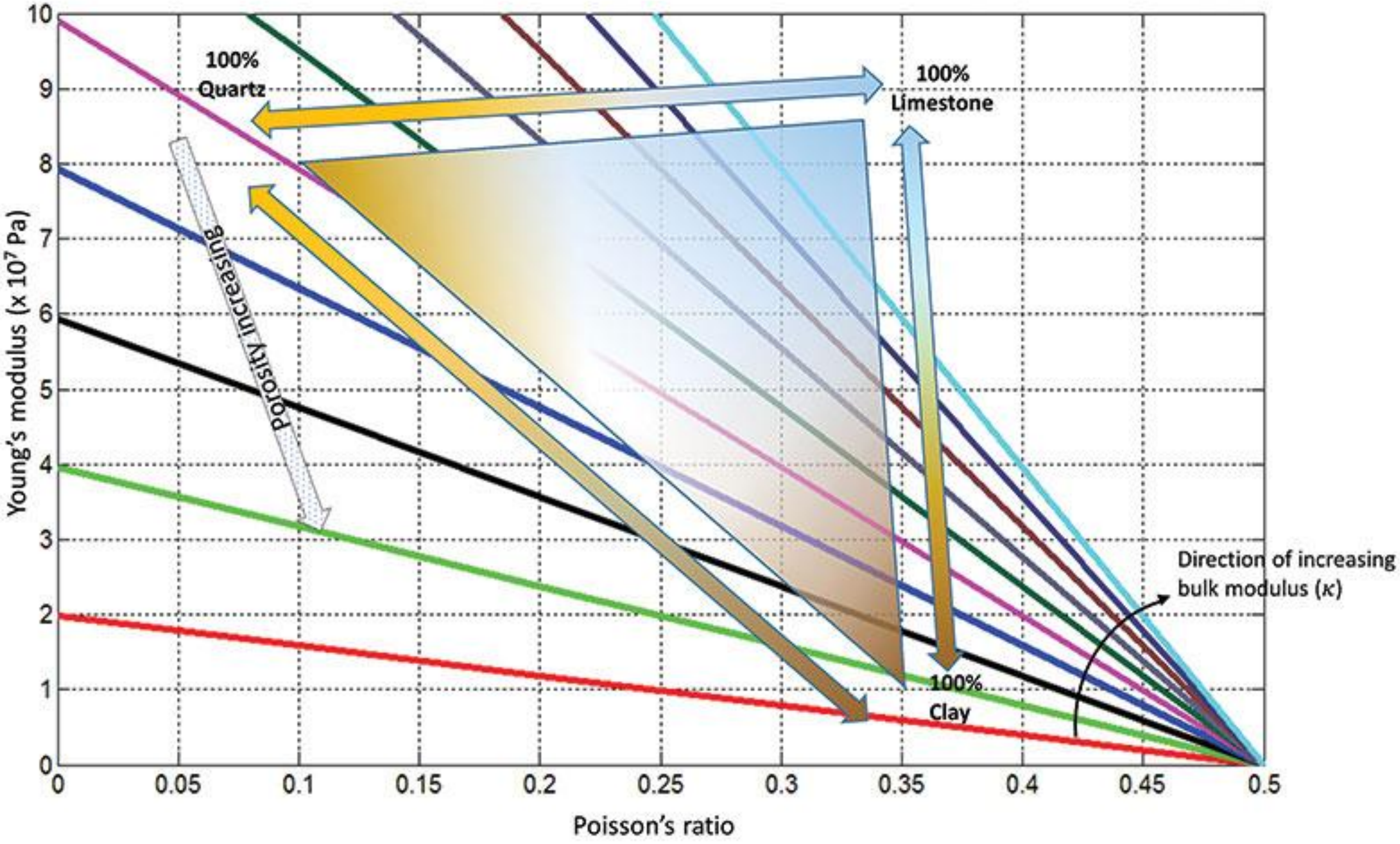

Figure 7. Rock physics template showing trends in Young's Modulus and Poisson's Ratio space. Lines of constant bulk modulus are shown increasing from red towards cyan.