The Geophysical Corner is a regular column in the EXPLORER, edited by Satinder Chopra, chief geophysicist for Arcis Seismic Solutions, TGS, Calgary, Canada, and a past AAPG-SEG Joint Distinguished Lecturer.

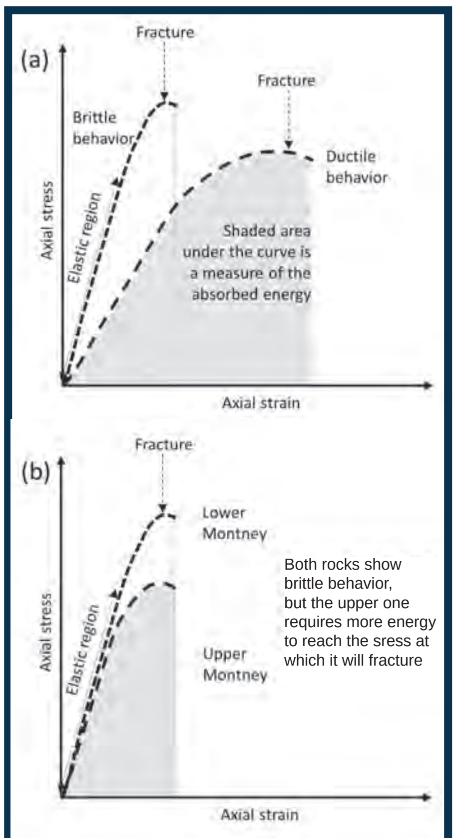


Figure 1: (a) Brittle versus ductile behavior of rock samples as seen on a stress-strain graph. (b) Both rocks showing brittle behavior, but one requires more energy to reach the stress level at which it will fracture.

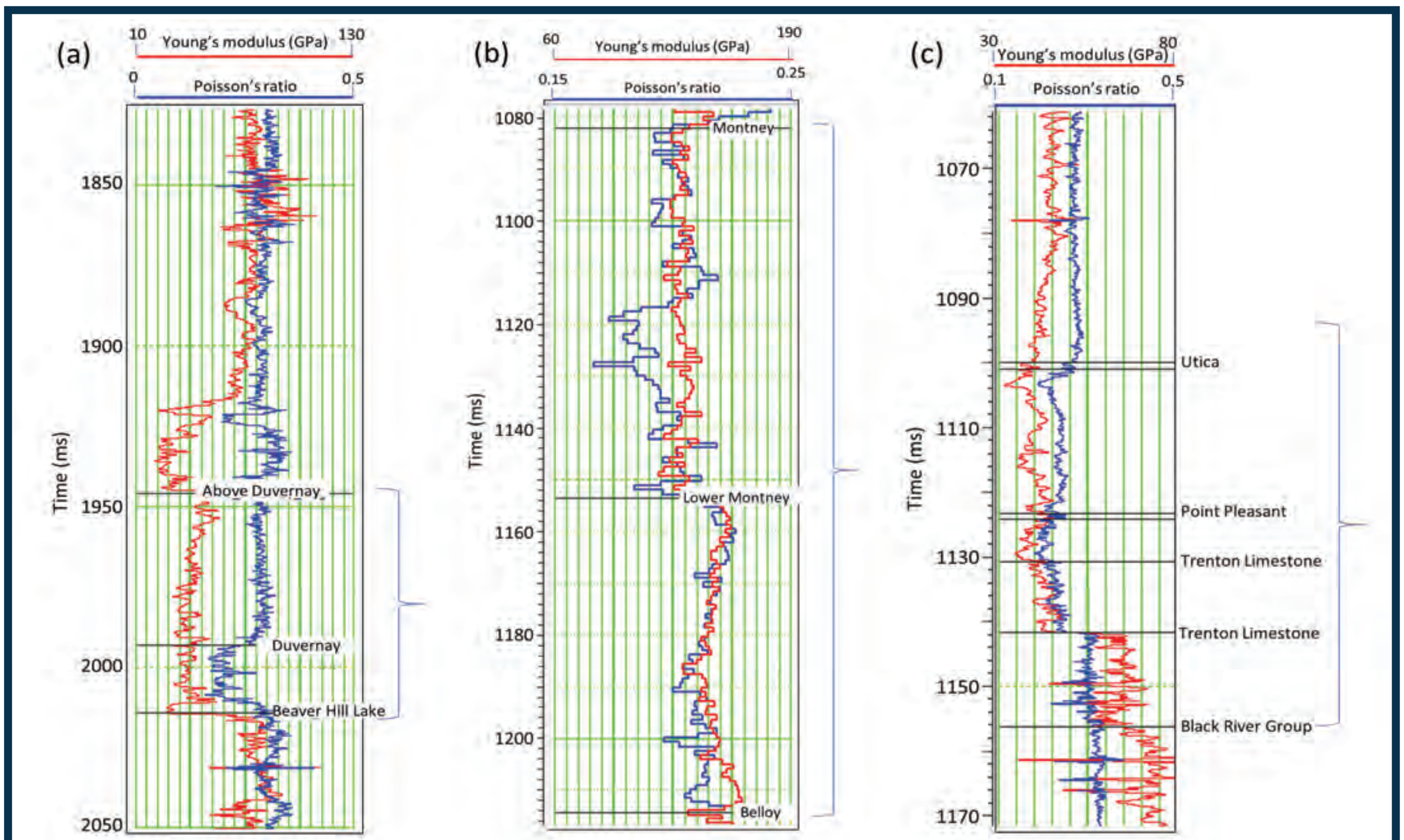
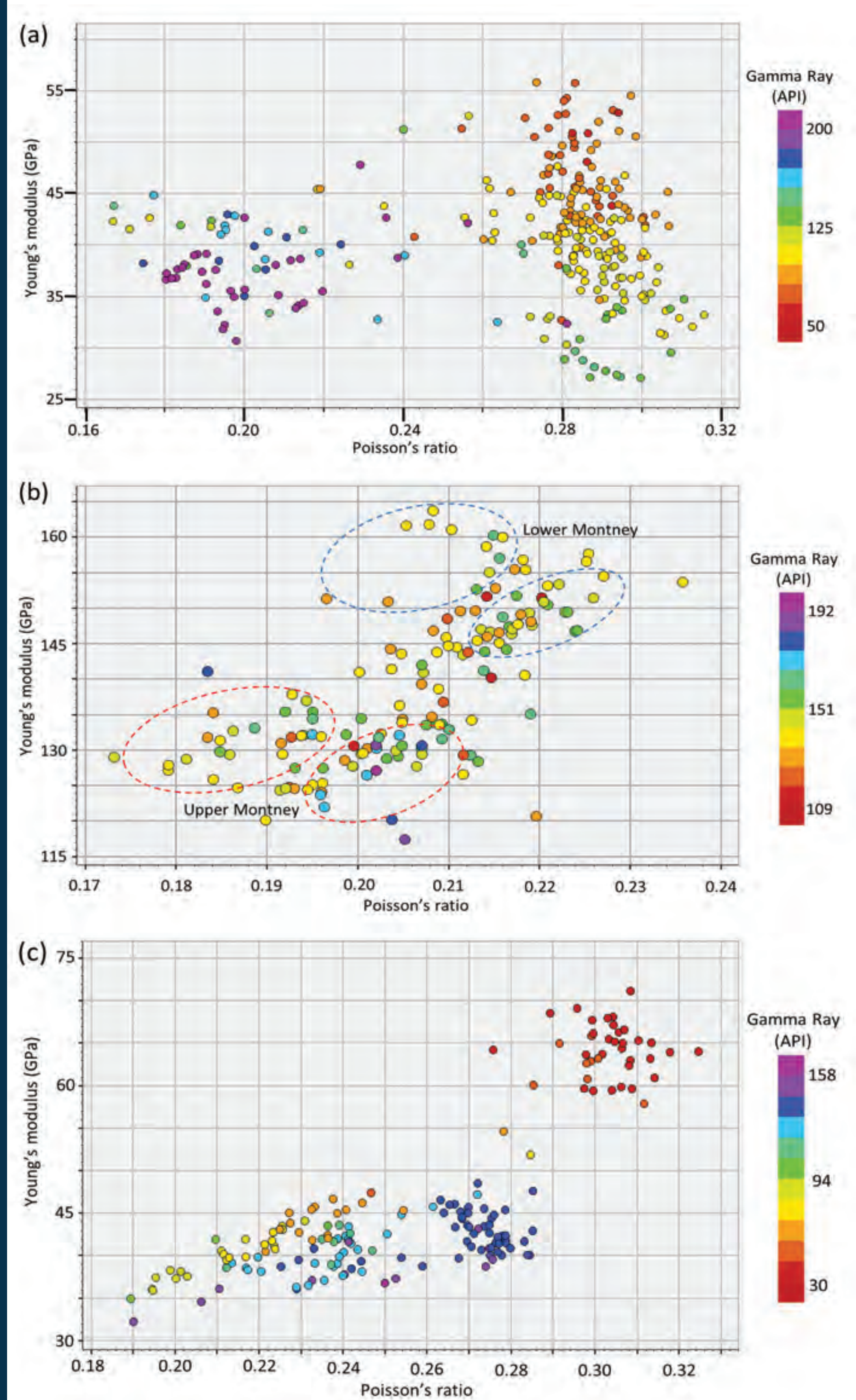


Figure 2 (above): shows the Young's modulus and Poisson's ratio curves for well data from (a) Duvernay shale in Kaybob area in central Alberta, Canada, (b) Montney shale in British Columbia, Canada, and (c) Utica shale from eastern Ohio, US. Notice a crossover between them only for Upper Montney. Such a crossover is not seen for the Duvernay and Utica shale intervals. The crossplots between Young's modulus and Poisson's ratio for well data shown in Figure 2 are shown in Figure 3 (below). The cluster points are all colour-coded with Gamma Ray values. Notice, the cluster points corresponding to the shale intervals of interest exhibit different values of Young's modulus and Poisson's ratio.



Misconceptions about Brittleness, and the Talk about Fracture Toughness

By SATINDER CHOPRA and RITESH KUMAR SHARMA

Hydraulic fracturing in very low permeability shale formations enhances the flow of fluids with the propagation of complex fractures through them, and is used for their exploitation. But effective propagation of complex fractures depends on a rock's ability to fail in a brittle manner. One might argue that all rocks should fail in a brittle manner when put under stress, as we do not expect any ductile behavior in rocks analogous to metals.

However, not all rocks exhibit similar brittle behavior, and thus we need to be able to quantify this property in rocks. Consequently, different methods have evolved over time, which are based on (a) mechanical properties, (b) their rock composition, and (c) the use of elastic parameters characterizing the rocks.

During the last decade, as the shale resource characterization has come to the fore, the term "brittleness" has become a buzzword. Interestingly, though we look for a way to quantify brittleness of rocks, there is no universally accepted definition or measurement of brittleness, and more than two dozen methods have been suggested by different authors under the aforementioned three categories. The underlying assumption in these methods is that a formation with high brittleness is easy to fracture, which is not always true. We have discussed the brittle versus ductile behavior of rocks in terms of stress-strain curves in our article published in the Geophysical Corner of the October 2015 issue. We include figure 1a here showing such a difference in behavior in terms of their energy absorption.

The methods in categories (a) and (b) above make measurements or carry out analysis on rock samples, and use that information to compute a brittleness measure. Methods under category (c) can determine elastic parameters from seismic data and after appropriate corrections compute a brittleness measure. As these methods yield spatial distribution of brittleness from 3-D seismic data, they are found to be attractive.

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Let us try and analyze the elastic parameters that are used in these methods.

Poisson's ratio is a measure of the *strength* of the rock, and Young's modulus is a measure of the *stiffness* of the rock. We assume that brittle rocks need lesser effort to break, so their Poisson's ratio should be low. At the same time, we associate high stiffness with the quality of the rock that would fracture easily and the fractures stay open, or its Young's modulus is high. Thus, we look for high

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Young's modulus and low Poisson's ratio for finding brittle pockets in our attempts at finding sweet spots in shale formations.

This combination of high Young's modulus and low Poisson's ratio as a measure of brittleness may not be true for all shale formations, as different shale formations exhibit different characteristics based on their mineralogy. In figure 2 we show the Young's modulus and Poisson's ratio curves and their cross plots for three separate shale formations. The first one is the Duvernay Formation in the Fox Creek area in central Alberta, Canada. The second example is from the Montney Formation in British Columbia, Canada, where the Upper and Lower Montney shales are cross-plotted. Notice the Lower Montney exhibits high Young's modulus and high Poisson's ratio, whereas the Upper Montney show low to intermediate Young's modulus and low Poisson's ratio. Our third example is from Utica Shale in Ohio, and it shows low Young's modulus and low Poisson's ratio.

Fracture Toughness

Let us go back to figure 1a and try and understand the different definitions in terms of the stress-strain diagram. A material is said to be brittle when it breaks without absorbing much energy, and without undergoing any significant deformation. On the stress-strain diagram we can distinguish a ductile rock that absorbs more energy from a brittle rock, which absorbs less energy. The difference in the areas under the curves is a measure of the energy difference. As we hear the term brittleness, the above distinction flashes in our minds and we believe that the brittle rock is easier to break.

There is fallacy in this belief.

If we look at the stress-strain curve for the Lower Montney that exhibits high Young's modulus and high Poisson's ratio, and compare it with Upper Montney that exhibits low Young's modulus and low Poisson's ratio, then they would look as shown in figure 1b. Notice, Upper Montney shale would fracture at a much lower stress than Lower Montney. What this suggests is that Upper Montney should be easier to fracture than the Lower Montney, but we still label Lower Montney as being more brittle.

Engineers and geomechanics experts cringe at the mention of "brittleness," as they know that geoscientists are confusing the definition of brittleness with something they imply as better fracability.

So, where do we go from here?

One way would be to think of the rock that we are looking at, to be brittle and at the same time require less energy to break. This could be understood by considering the stress state at the tip of a propagating fracture. A rock can withstand fracture tip stresses up to a critical value, which is referred to as the critical stress intensity factor; this ability of a rock to resist fracturing and propagation of pre-existing fractures is known as "fracture toughness." It is an intrinsic rock property.

The consequent strain energy build up needs to reach its critical value, before a pre-existing fracture propagates. This balancing of the critical stress intensity and critical strain energy release rate can help determine fracture toughness in the tensile mode of fracture propagation that we are interested in. The fracture toughness thus emerges as a measure of a rock to resist fracture growth. Rocks with low fracture toughness promote fracture propagation.

Determining Fracture Toughness

Finally, as answer to the question above, we need to develop a way to determine fracture toughness from seismic data. This would help us determine brittle pockets that exhibit lower fracture toughness, and thus represent more meaningful sweet spots that engineers describe as fracture efficient.

In figure 3 we show a horizon slice from an inverse fracture toughness volume from the Duvernay Formation. Overlaid on this display is the induced seismicity data, which has been collected to monitor the seismicity in the area. Notice the seismicity trend matches the higher values of inverse fracture toughness, and provides the required confidence in its interpretation.

In conclusion, fracture toughness measures should be preferred over brittleness, as the latter does not yield information about fracability of the formation. Fracture toughness measures from seismic data would allow more confident picking of sweet spots on 3-D seismic data volumes, and the subsequent accurate planning and designing of hydraulic fracturing. E

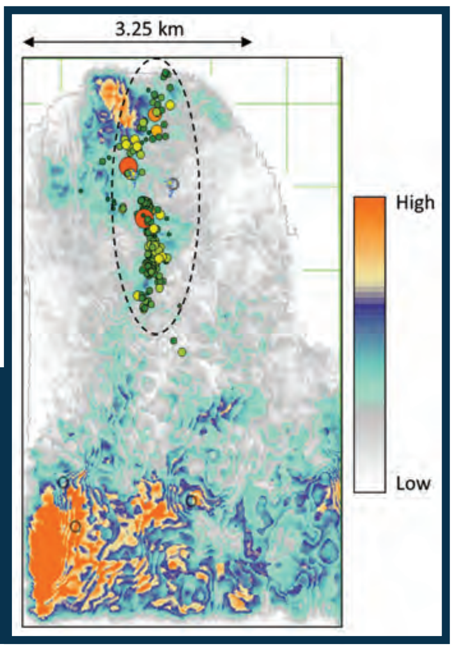

Figure 4: Horizon slice from inverse fracture toughness measure volume for the Duvernay formation in the Fox Creek area in central Alberta, Canada. Notice, the high values of inverse fracture toughness measure (or low values of fracture toughness measure) correlate well with the induced seismicity data overlaid on the display. Induced seismicity data is courtesy of Repsol Oil and Gas, Canada.