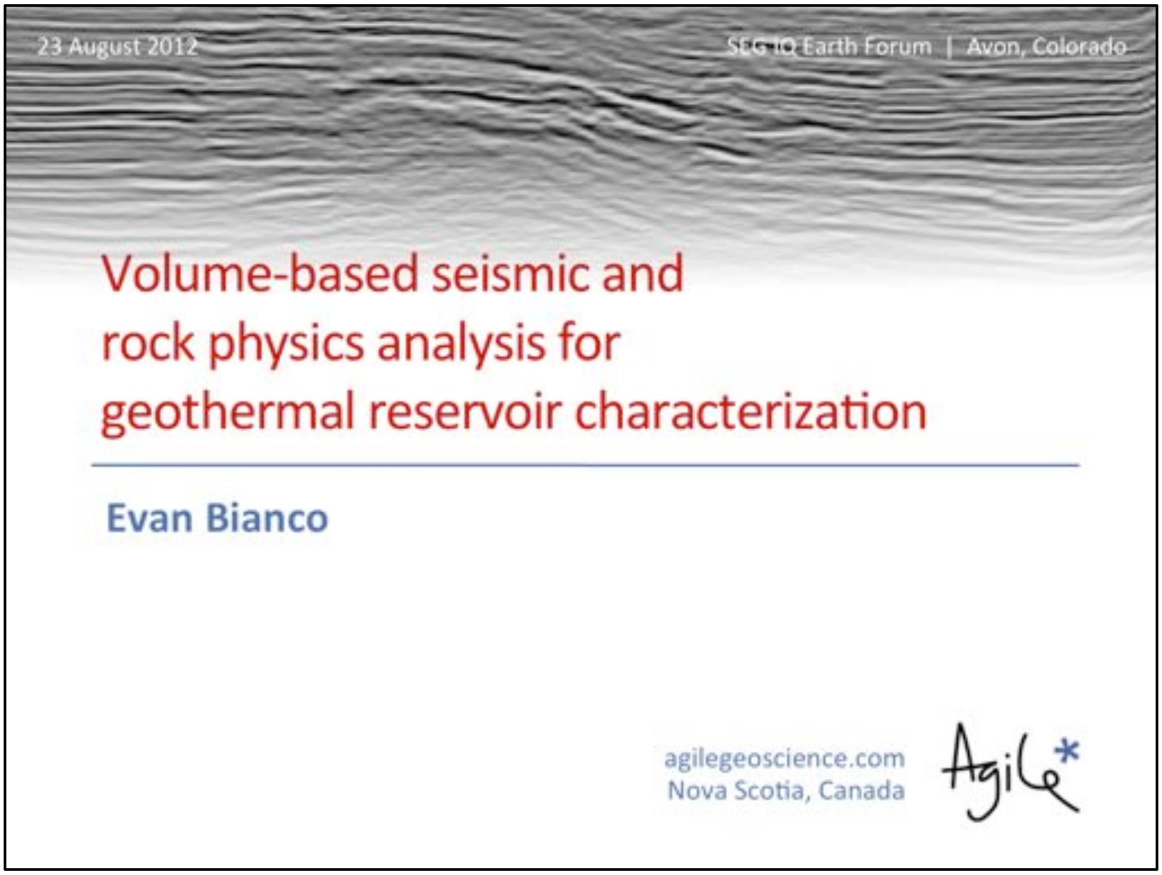
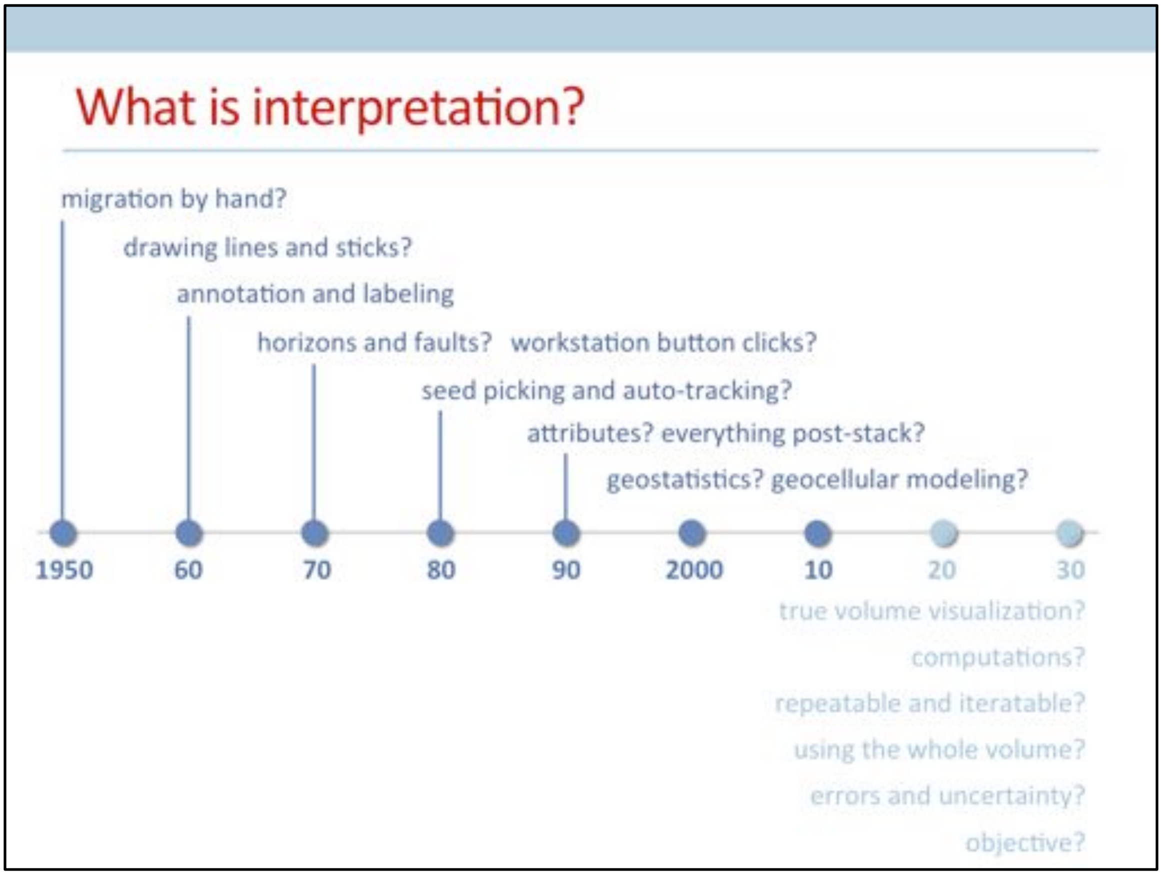
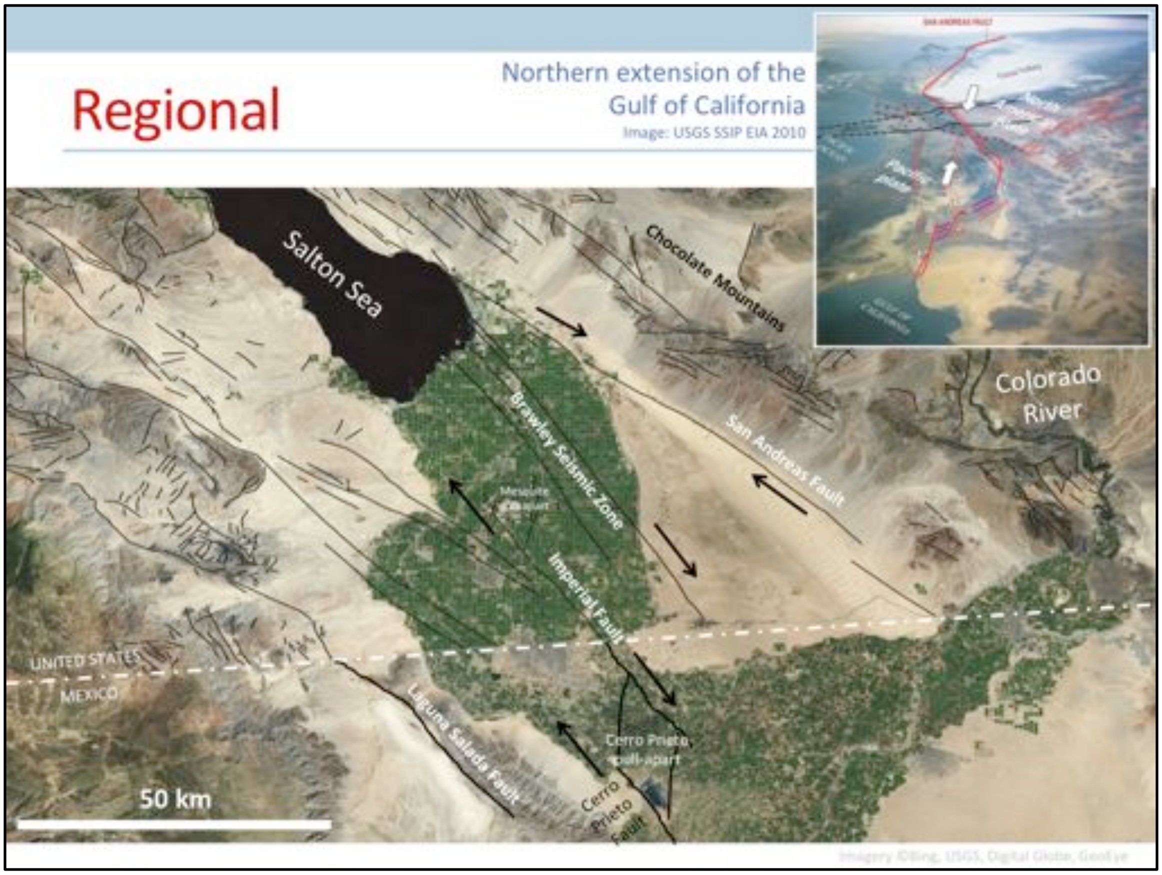



This is a short talk I gave in August 2012 at the SEG IQ Earth Forum in Avon Colorado. I talked about seismic techniques for studying geothermal reservoirs.

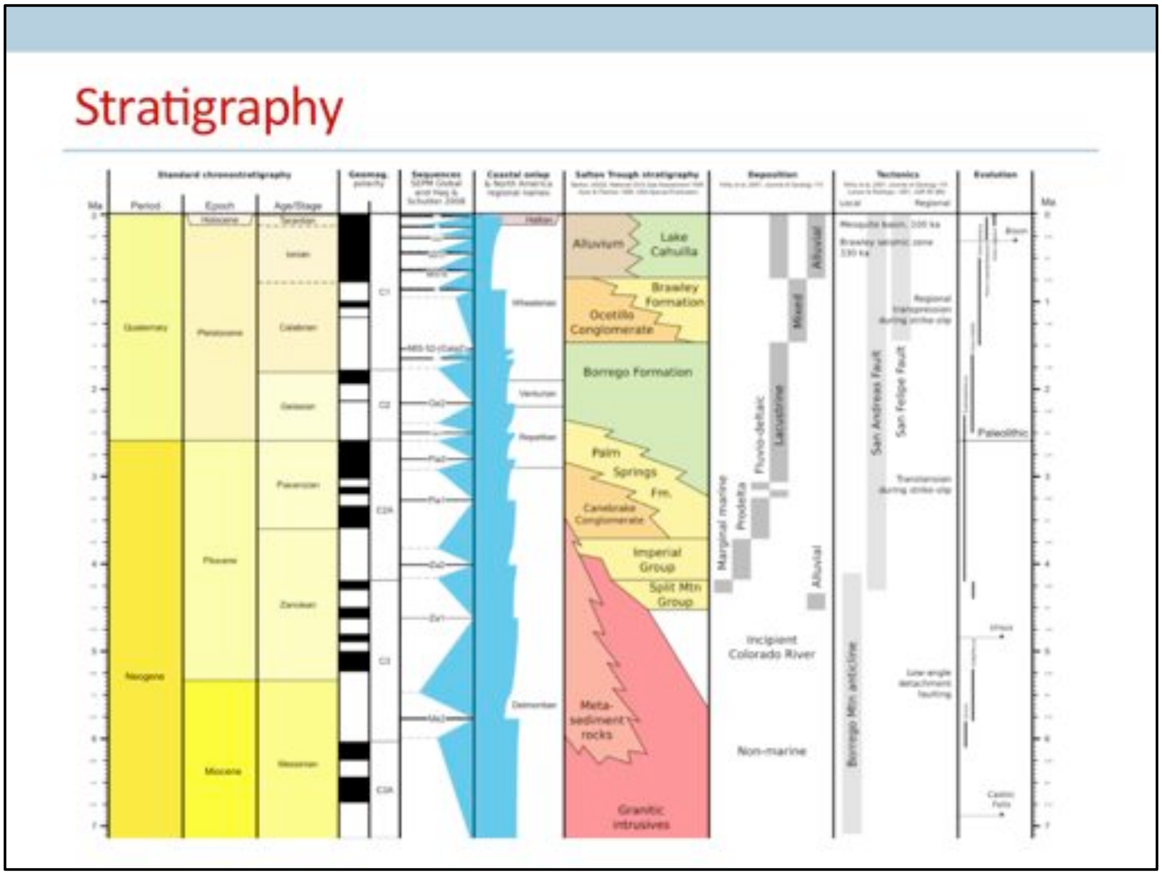



I don't like the word interpretation because I don't it's specific enough to describe all the work that we have to do now on the components of our mythical interpretation machine. Does interpretation mean pre-stack work? What about migration? Is that interpretation? It depends on who you ask. The act of interpreting as a thing we do, is actually subject to interpretation. What's that about?

Some people say that there is an art to interpretation. I would like to make a correction to that. I say, Seismic interpretation IS ART. When I mean art, I don't mean painting. Art is anything that is difficult or impossible for someone else to reproduce. I think we  must minimize our dependence on things that are hard to reproduce. The opposite of art might be the black box algorithm, cold and lifeless, which might sound threatening, but I wish to show you that there is enough art, creativity and ingenuity that goes into making an algorithm, and it is to that approach where we should shift our attention.



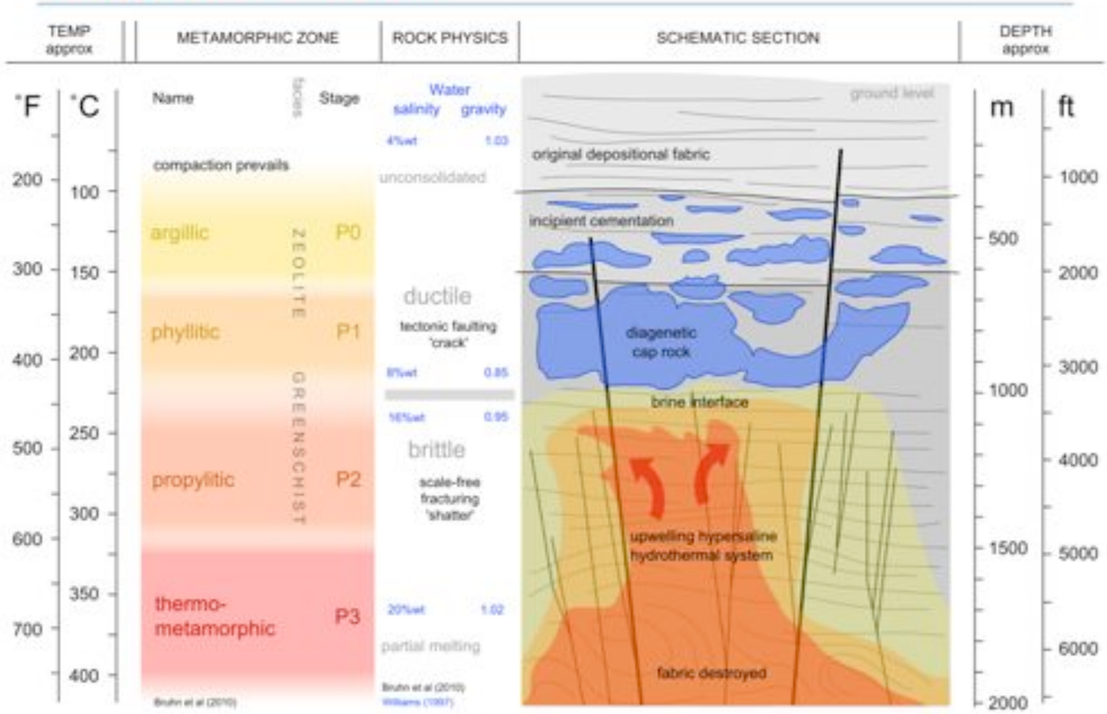

Here are some salient features of the regional setting. The project lies in the Salton Trough, which is the northern extension of the Gulf of California rift shown here in the top right. The project is in a small pull-apart basin above an active rift. It's a major strike-slip zone, obviously, there is active sedimentation from the Chocolate Mountains to the north.



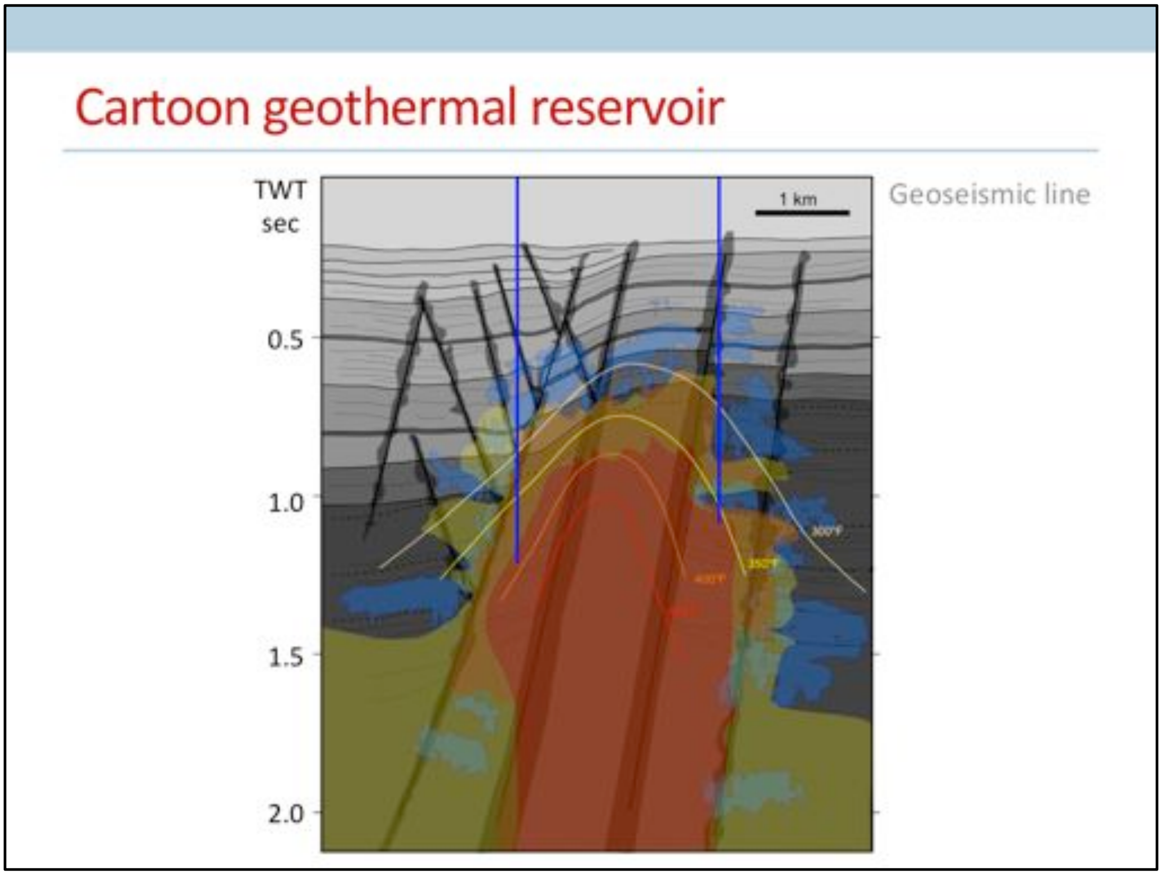

**Stratigraphic column. Rapidly subsiding, active pull apart. Overall there is a marine to alluvial regression.**

The operator in this area started drilling for hot water based on a temperature anomaly (no seismic data was used in drilling production wells). They drill 17 inch boreholes (which is massive compared to oil and gas operations to allow as much hot water into the borehole as possible. There is a steam to electricity power plant right at surface. After having some curiosities about inconsistent production rates, they invested in a 3D seismic survey, obtaining their first images of the reservoir.

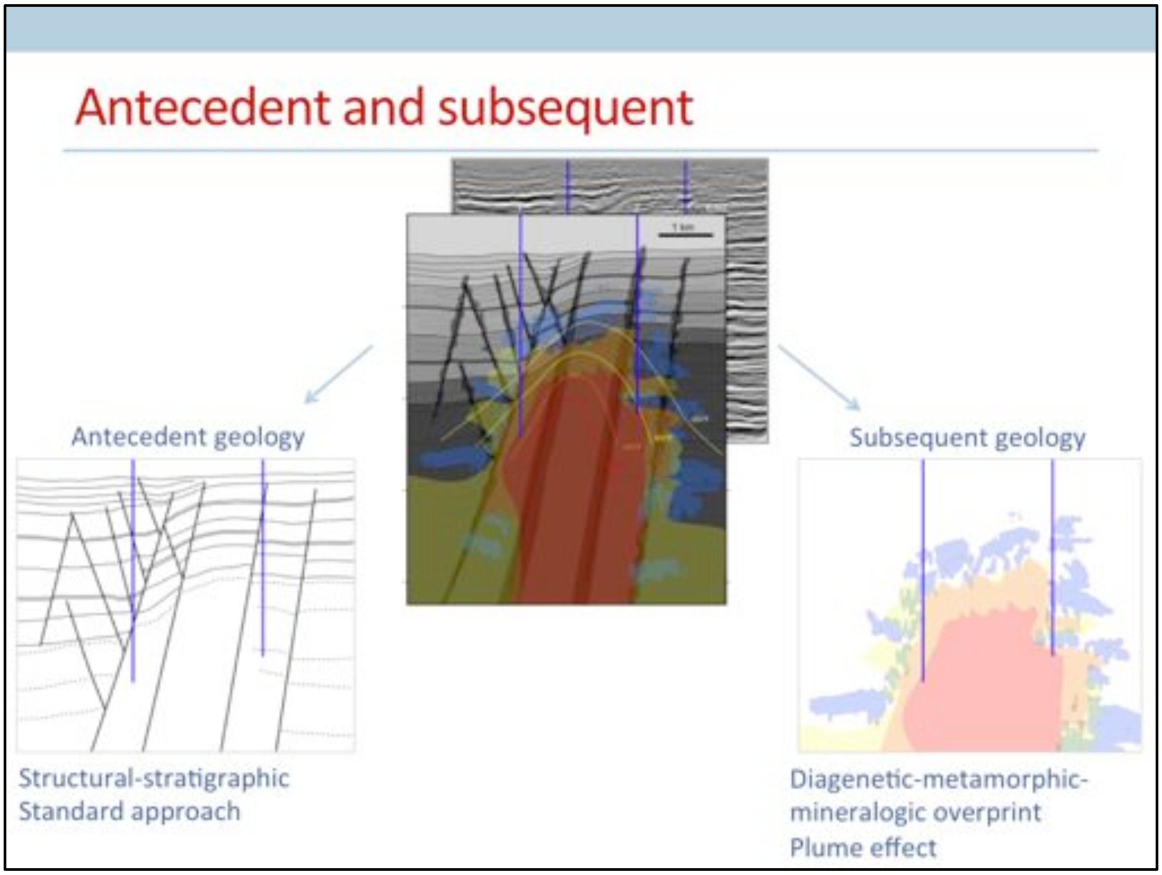
# Diagenetic model



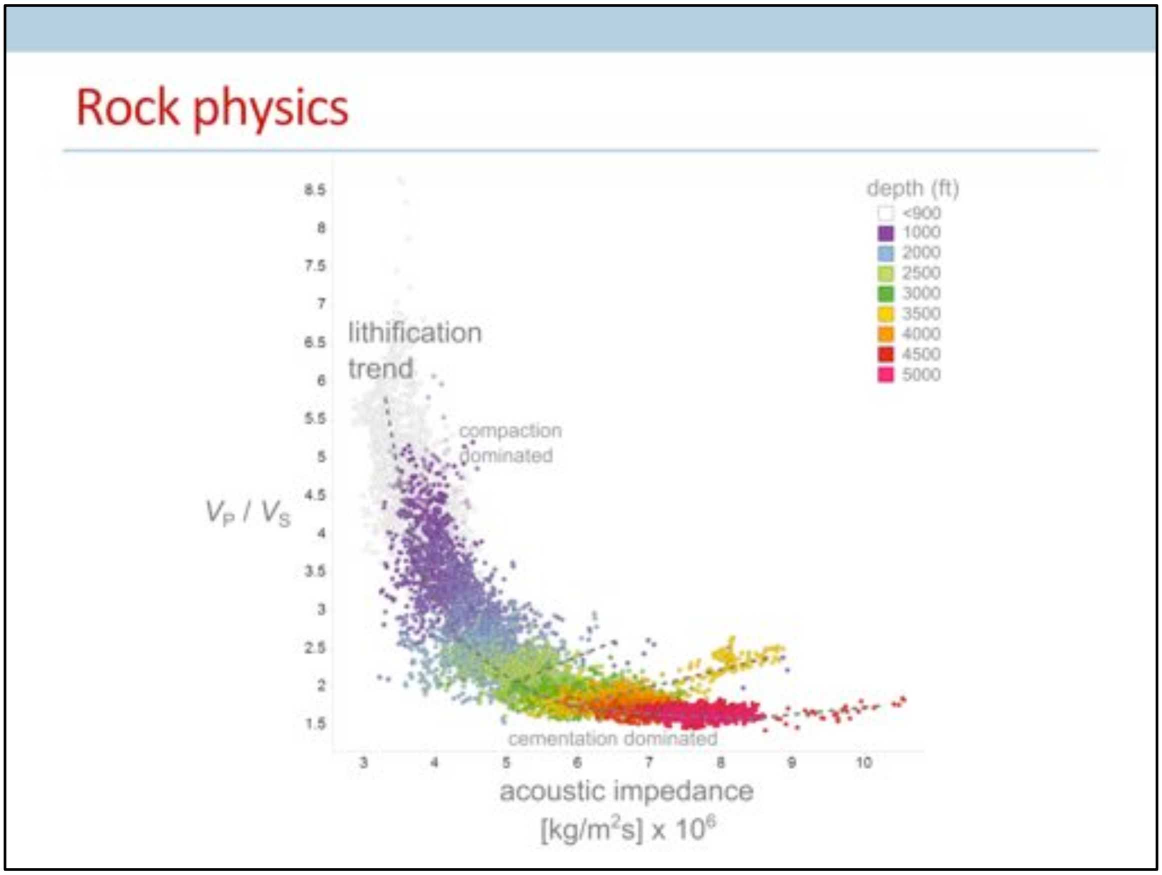

This schematic is  the first step in building a field-specific model for the low-grade metamorphism, which will eventually help predict reservoir quality. The basic idea is that there are paragenetic zones, driven by temperature, and these zones have different geomechanical properties. The propylitic zone is the most favourable for hydrothermal energy systems.  When hot hypersaline circulating fluids  cool, they precipitate  out cements into the host rock especially in the most porous formations. We call this the cap rock, shown here in blue, and has this patchy, here and there look to it.



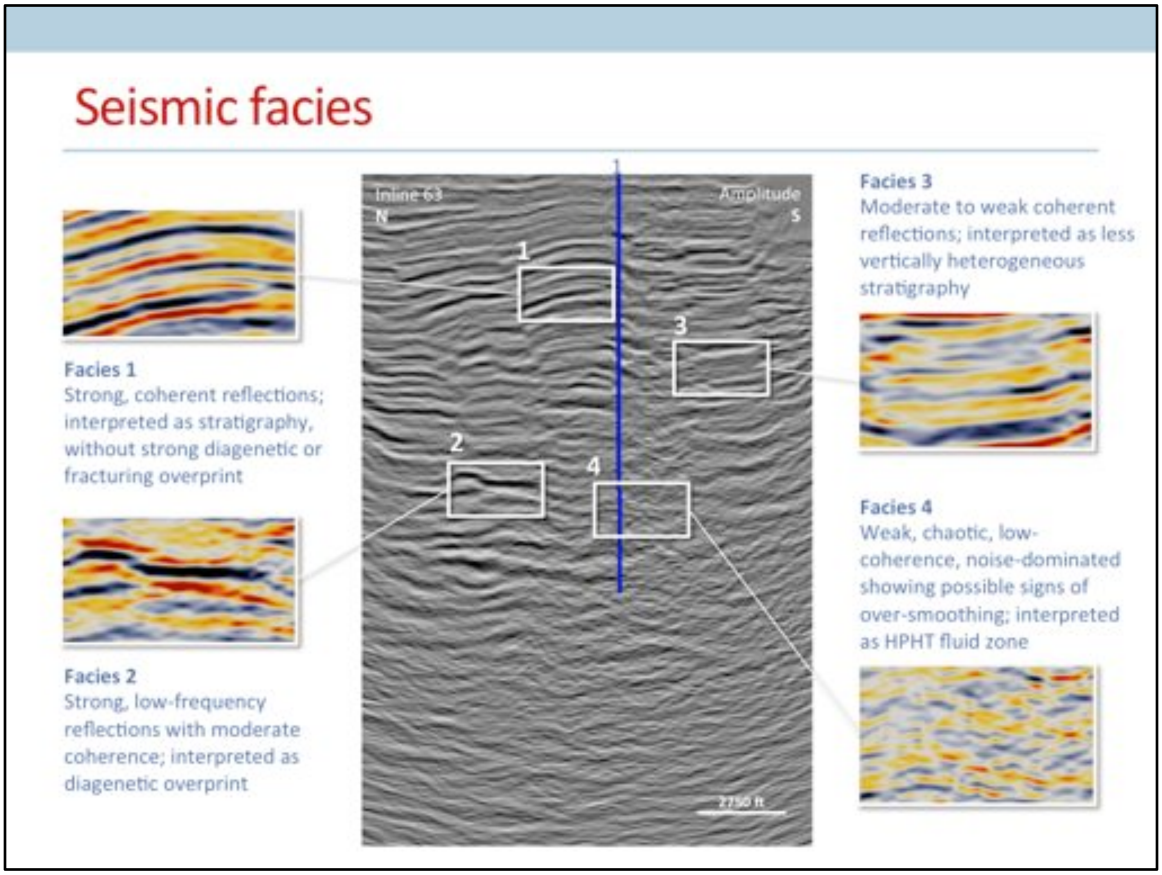

And you can see how structurally complex it is. The fault and fracture network governs, to some extent the distribution and rise of heat, and the precipitation of cements as hyper saline brine are circulated and cooled (shown in blue).



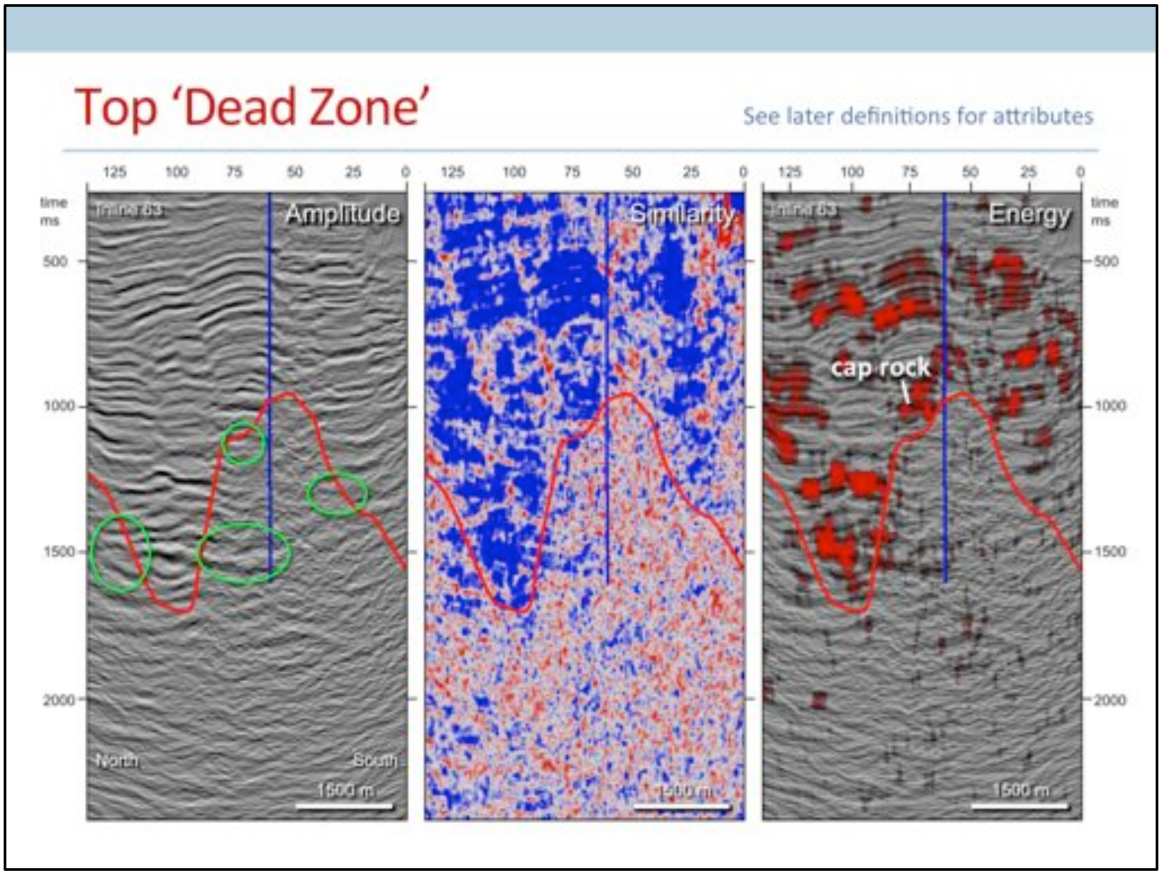

Conceptually speaking this geothermal system can be separated into two parts. The antecedent geology; the structural and stratigraphic framework, which we could target with a standard seismic interpretation approach, and the subsequent geology from the hydrothermal present day siliciclastic metamorphism and diagenesis. A conventional seismic interpretation (picking reflectors and faults) would not only be quite challenging n this setting, but it may in fact us tell  us very little about the system components like temperature, brittleness, cementation, grain framework, and greenschist metamorphism. Now, try making a time structure map out of the stuff on the right, and you'll fail.




Here is what one well looks like in the standard Vp/Vs Acoustic impedance cross plot. The overall depositional or lithification trend is offset or perturbed with there is diagenesis. The cementation effect is a significant deflection away from the trend.

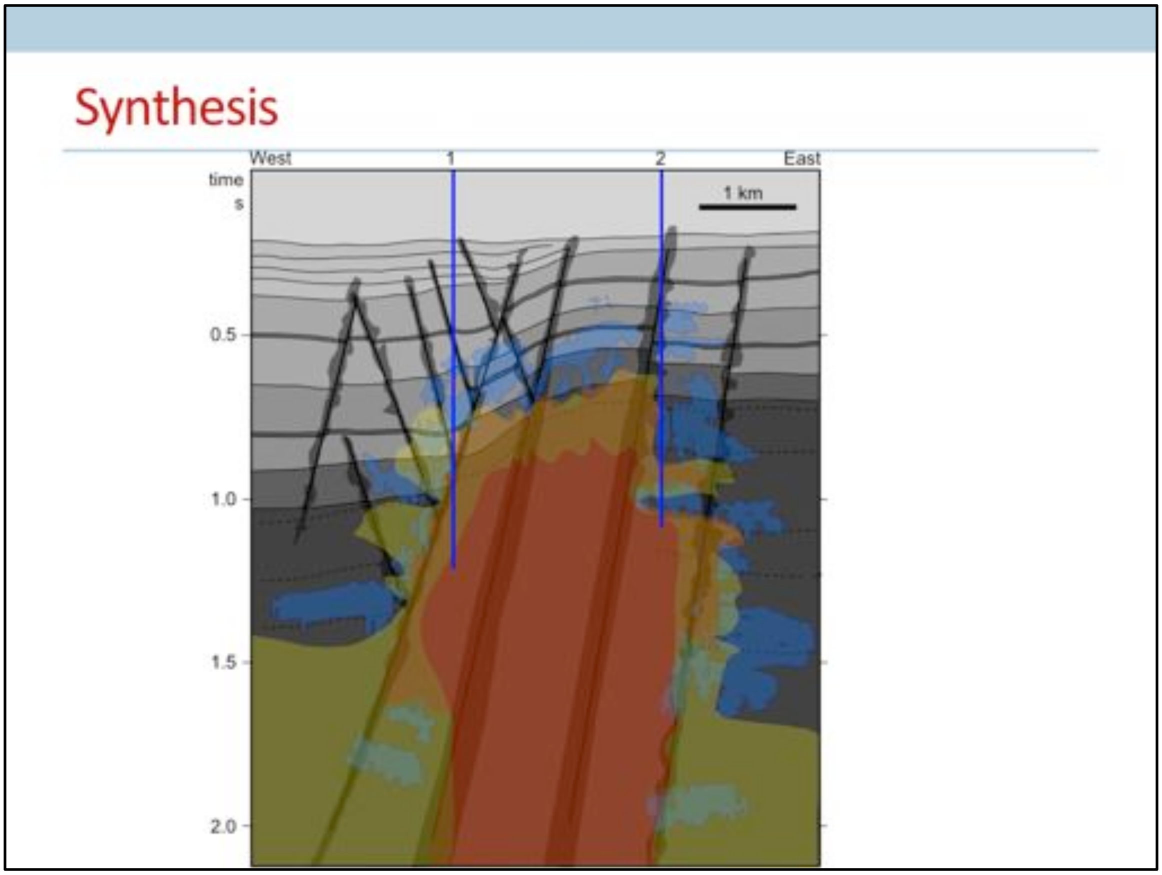



In our early viewing of the data, we recognized at least 4 sets of seismic reflection patterns. And we wholehearted hereby call them *facies*. For all *interpreters* it's at least a little bit novel to say, "what are my seismic facies?" before you even try to pick reflections. Again, this is what I would call essential in any seismic workflow, seldom practiced, we form an impression of an earth model before we even touch it with a digitizer, paintbrush, or pencil crayon.



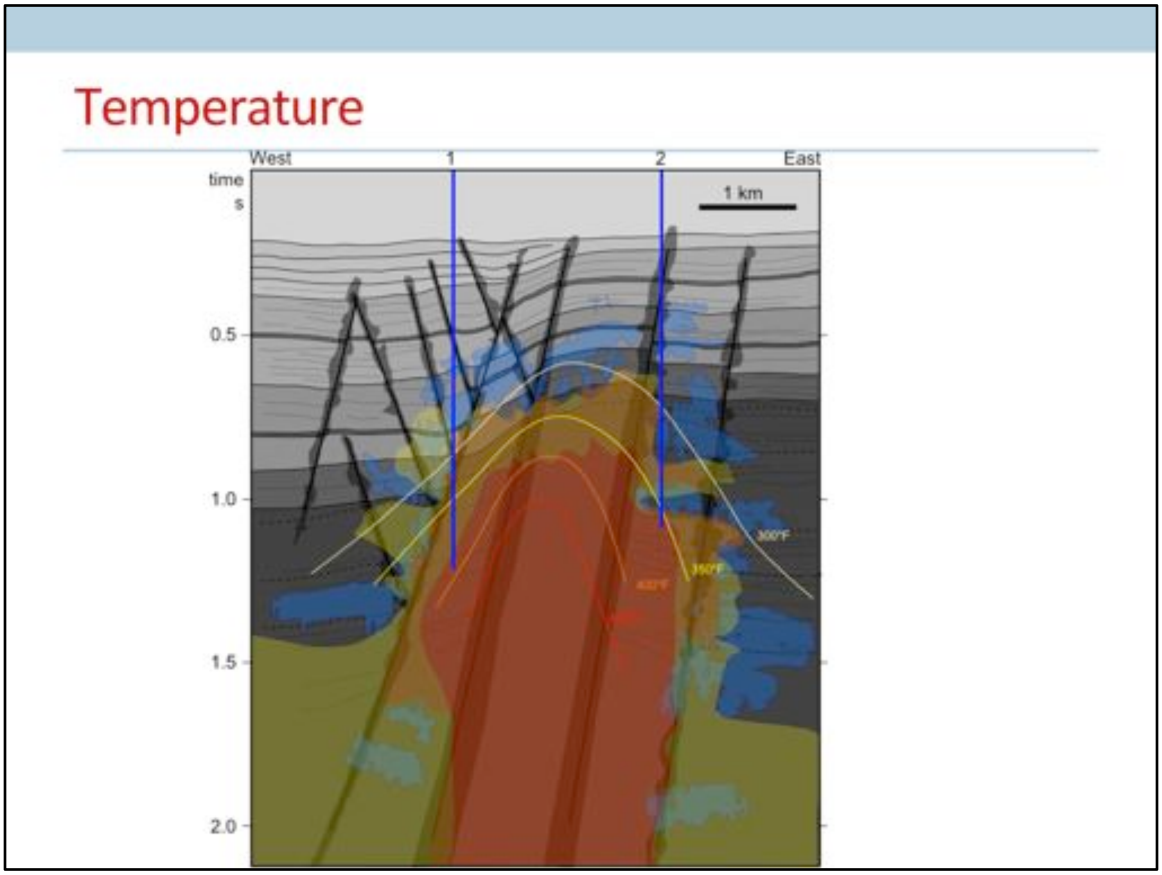

Traditional horizon picking means, picking events or reflections, whereas this is picking a facies boundary. It's a akin to picking top of dirty salt, say in the Gulf of Mexico. Not easy to do on a workstation. There is nothing automatic about it, and it's far too subjective. Nevertheless, in our initial work, the top of the low semblance zone (which we colloquially call the top of the dead zone), was mapped and examined for additional attribute anomalies.

The attributes amplitude, similarity, and energy, all, in their own graphical way, delineate this dead zone. Each one, shows a unique element in the geothermal system. Amplitude shows the stratigraphy / layering, similarity shows discontinuities (faults), and a low semblance zone (which we infer as the moderately metamorphosed zone), and the energy attribute gives these patchy blobs of high energy at the periphery of the deadzone. We believe this represents the stiffened sandstones; where hot brines have cooled and precipitated salts, cementing up the grain-to-grain contacts, making the lithology more acoustically heterogeneous, and hence more reflective.




When we add everything together we have a basis for comparison with the diagenetic model. We may choose to investigate some of these possible patterns further: how do other wells perform in a similar framework? Good production data are key for making this comparison.

We stack the layers to help us understand where the most favorable zones might be
- Below cap rock (blue)
- Close to major faults
- In reservoir zone (red)
- In hanging wall of growth fault




Adding isotherms (from well data) does not undermine our interpretation. In fact, you might even say that the sparse temperature measurement is like smoothed sampling of the geothermal system. I wouldn't go so far to say that we can image temperature using seismic, because the "temperature" is coupled with a whole whack of other physical and chemical process that effect the rock properties and determine the seismic response. Temperature is an alibi.

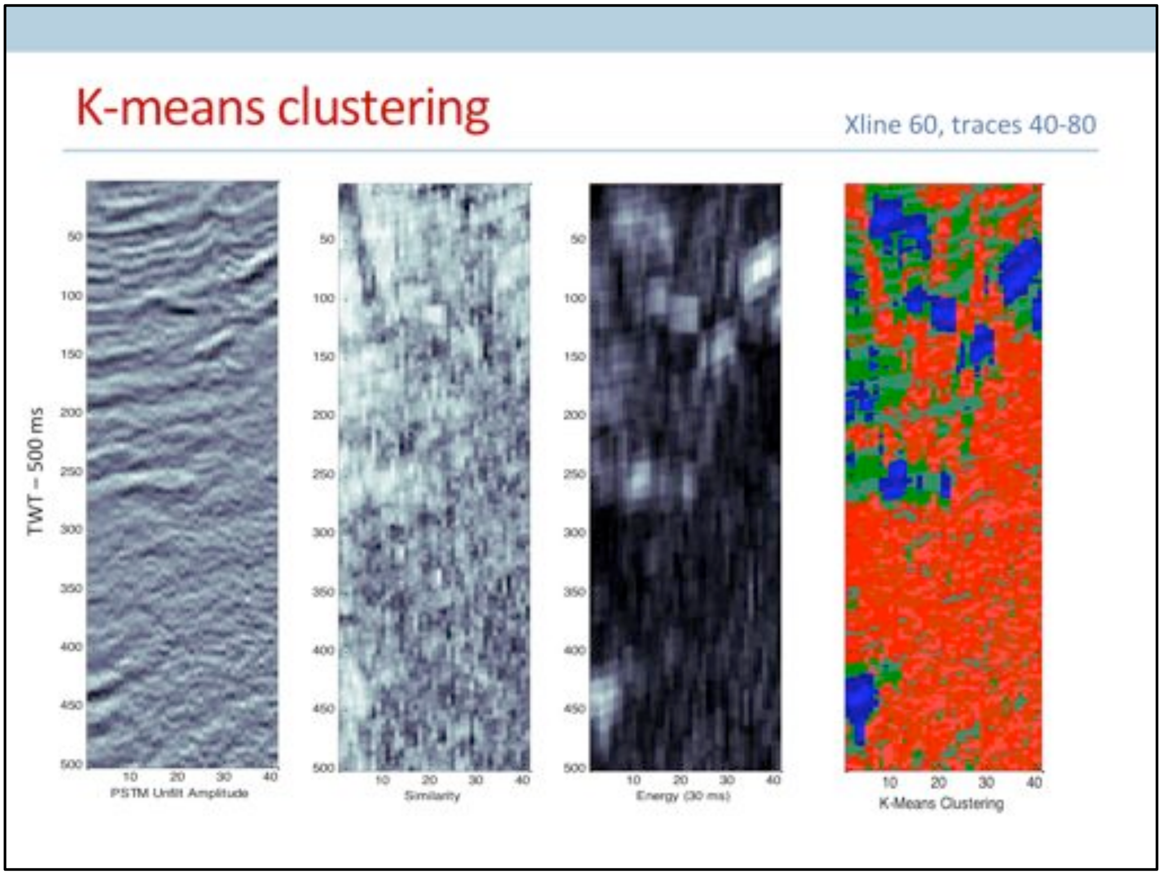
This exercise of exploring the post-stack seismic attribute space (of which there are many other attributes that I either discarded or didn't try) is one that allows us to get at detailed signals that corroborate with the diagenetic model. The problem however, is that I drew these image layers painstakingly in a graphic editor, Inkscape.

But we can do more with these use these three attributes. We can be more systematic with them, less artistic

I set this aside, this image and try to move beyond it, but remember this notion that we have arrived at **four main facies** using **three attributes.**

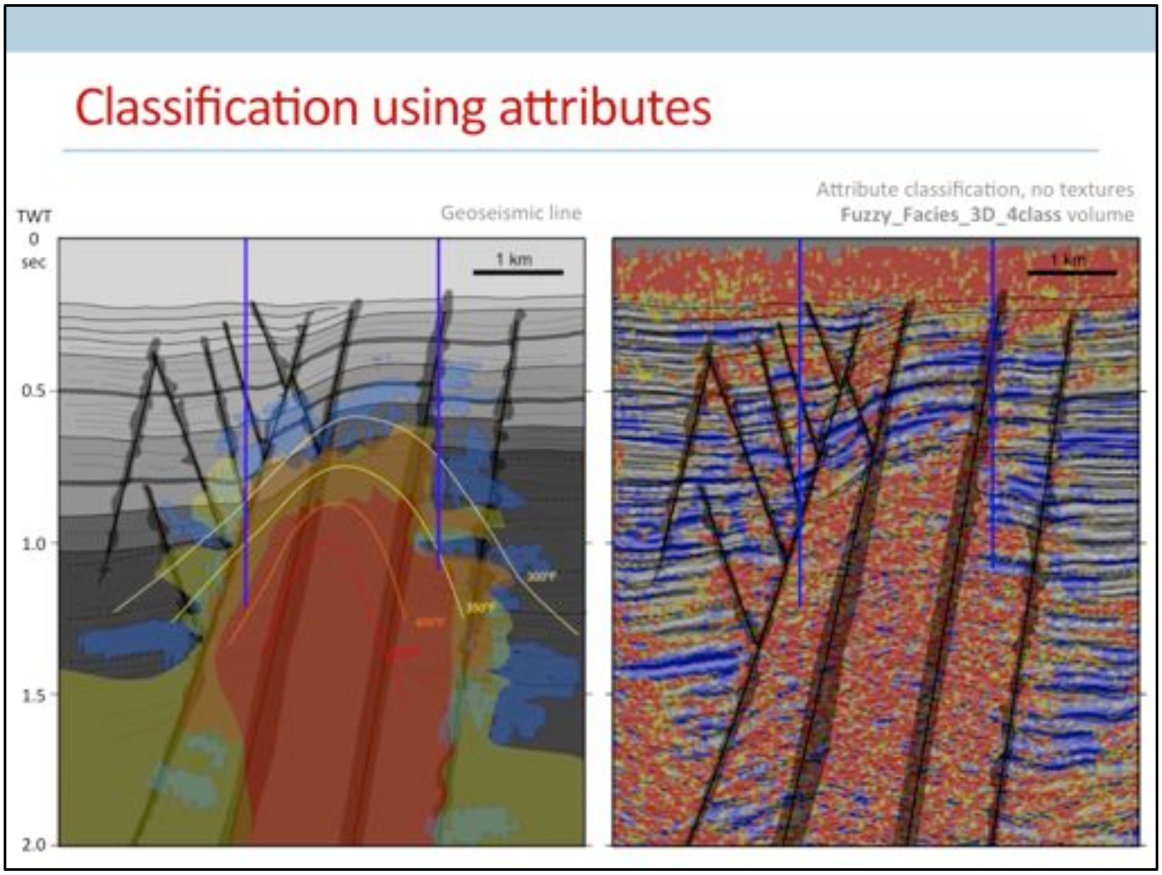

Any ensemble of attributes, whether it is the three that I just showed you, or 7 of your favorite combinations of attributes; prestack (like intercept and gradient), or post stack like an ant-tracker or spectral decomposition volumes, all are co-located for each point in space, at each pixel. As such, any number of attribute dimensions can be used to unique classify each point in space. How many attributes should you use? How many classes are there? I don't think there is a general answer of even a rule of thumb. It depends on how the data are clustered.

The concentric ellipses around each cluster denote this notion that each point can be assigned a probability of belonging to each cluster. The points on the periphery of the cluster are assigned lower probability, the points near the center of mass of the cluster are high probability.

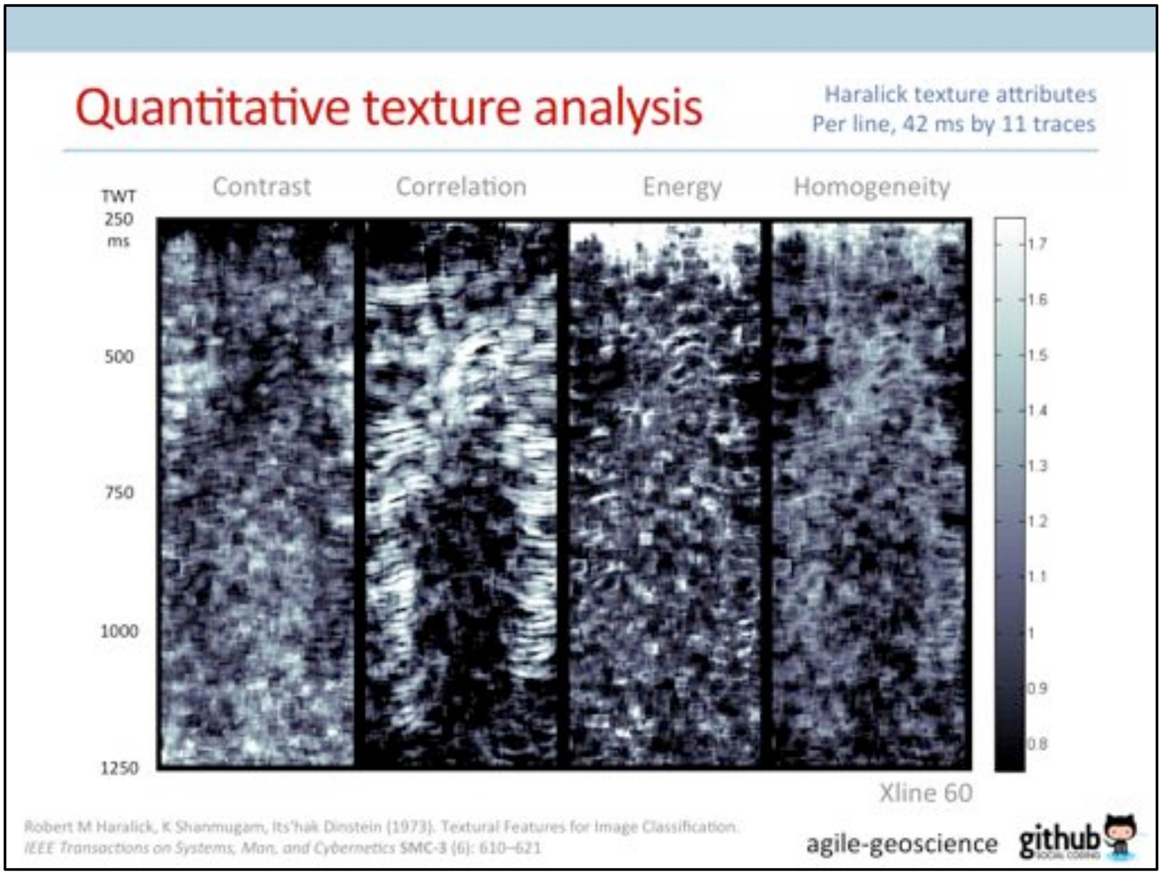



This is an example using the three attributes we used to build our cartoon: Amplitude, Similarity, and Energy. Clustering them into one of four clusters, and we get the colored classes on the right.

Now if I simply assign a new color to each class so that it matches how I have drawn my cartoon. We can make a direct comparison…




To help, I have made the amplitude data appear behind the classification on the right, which I have made semi transparent. Also, I have overlain the drawn fault zones for easier comparison. First shot at it, it seems to be a decent representation of the system, but not perfect. It seems like we are over estimating the blue cap rock facies, the near surface is failing, and the low fold regions on the edges is struggling as well.



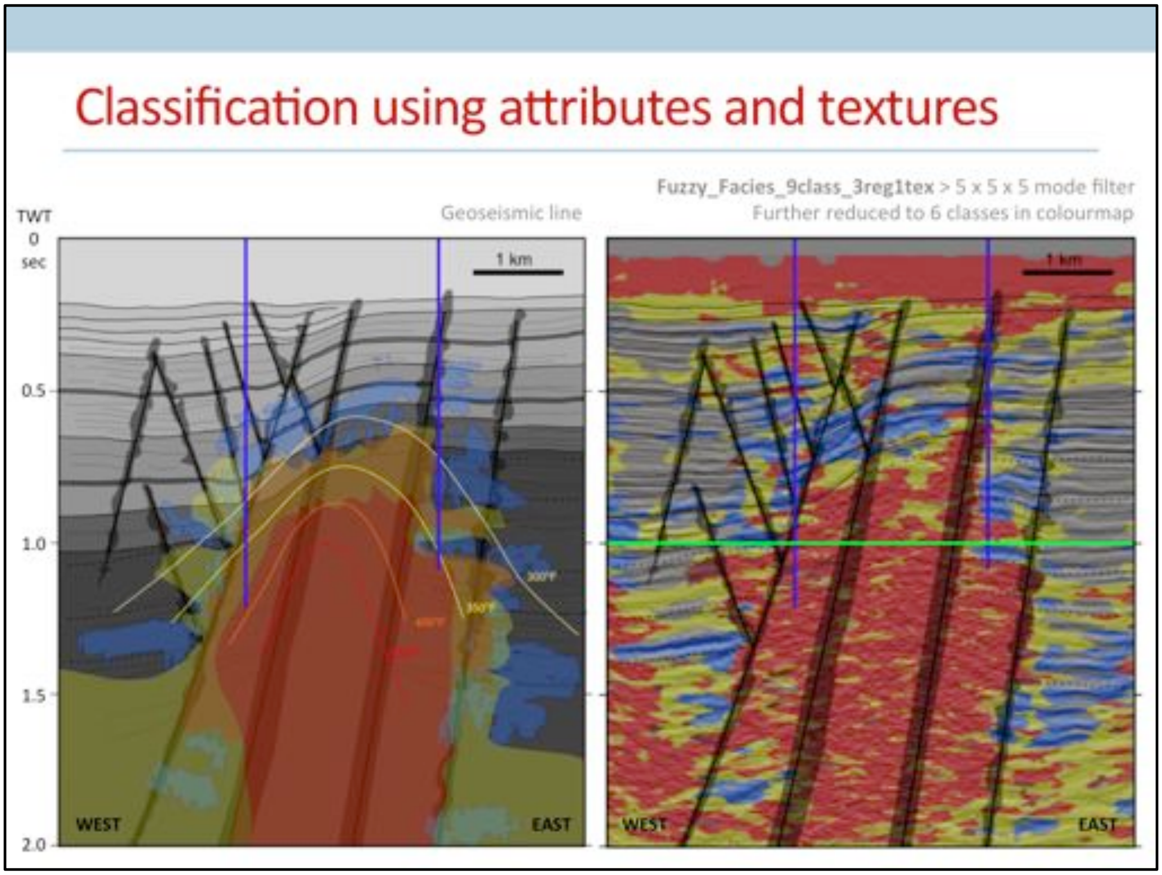

To attack the complexity of the objects and shapes suggested by the diagenetic model and we wanted to do more to quantify and classify them.

We used an algorithm that measures local statistical properties of patterned images, called Haralick textures. Which I blogged about recently:
[http://www.agilegeoscience.com/journal/2012/6/29/fabric-textures.html](http://www.agilegeoscience.com/journal/2012/6/29/fabric-textures.html)

Haralick textures are computed statistics of grey level co-occurrence matrices (GLCM); vectorized pixel-by-pixel comparisons of the amplitude values in an image.

The gist is that we are saying; give me four numbers that describe the texture in the small neighbourhood of every pixel. The result is four additional attributes. Four additional dimensions to release into the clustering problem.

And this output shows us that there is textures in these textures, textures at a larger scale. There are many length scales that the seismic image might be texturally sensitive to.

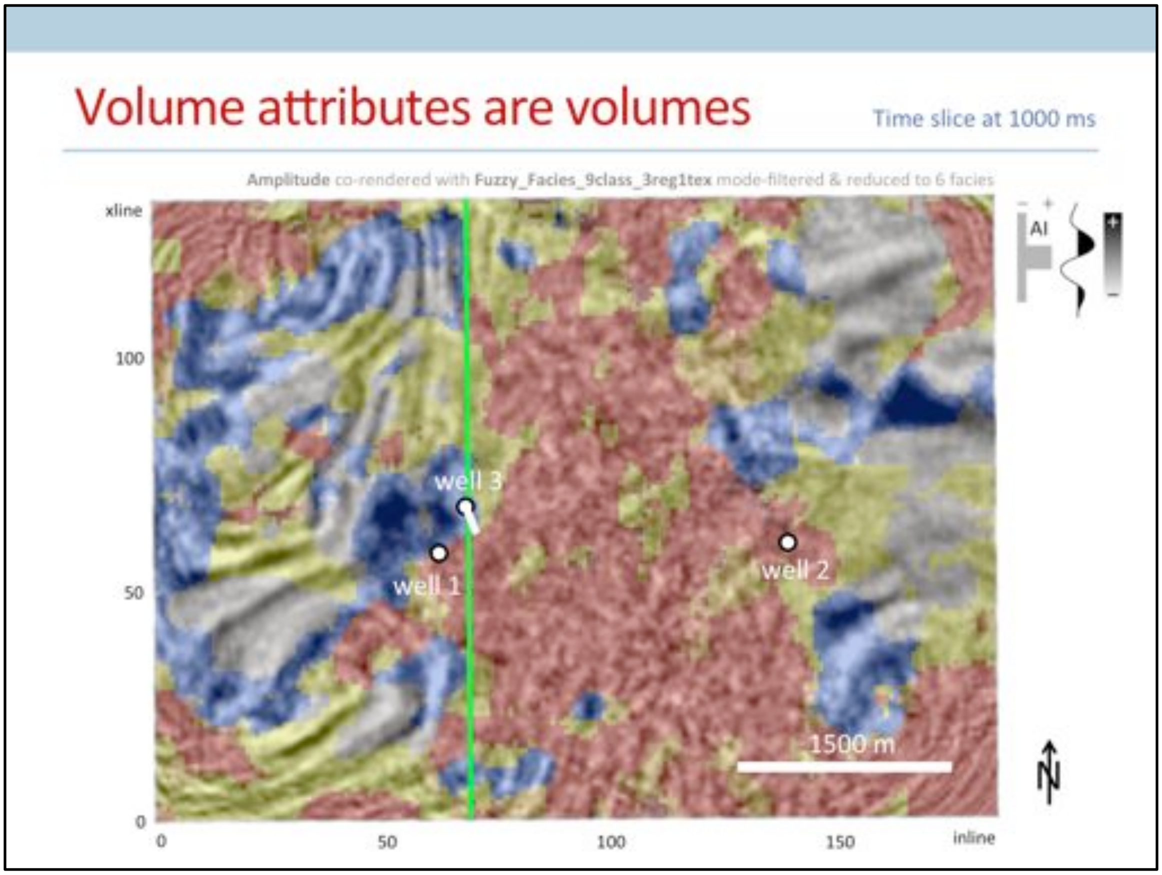



These textures now become four more attributes (for each pixel) that we can add back into the clustering algorithm

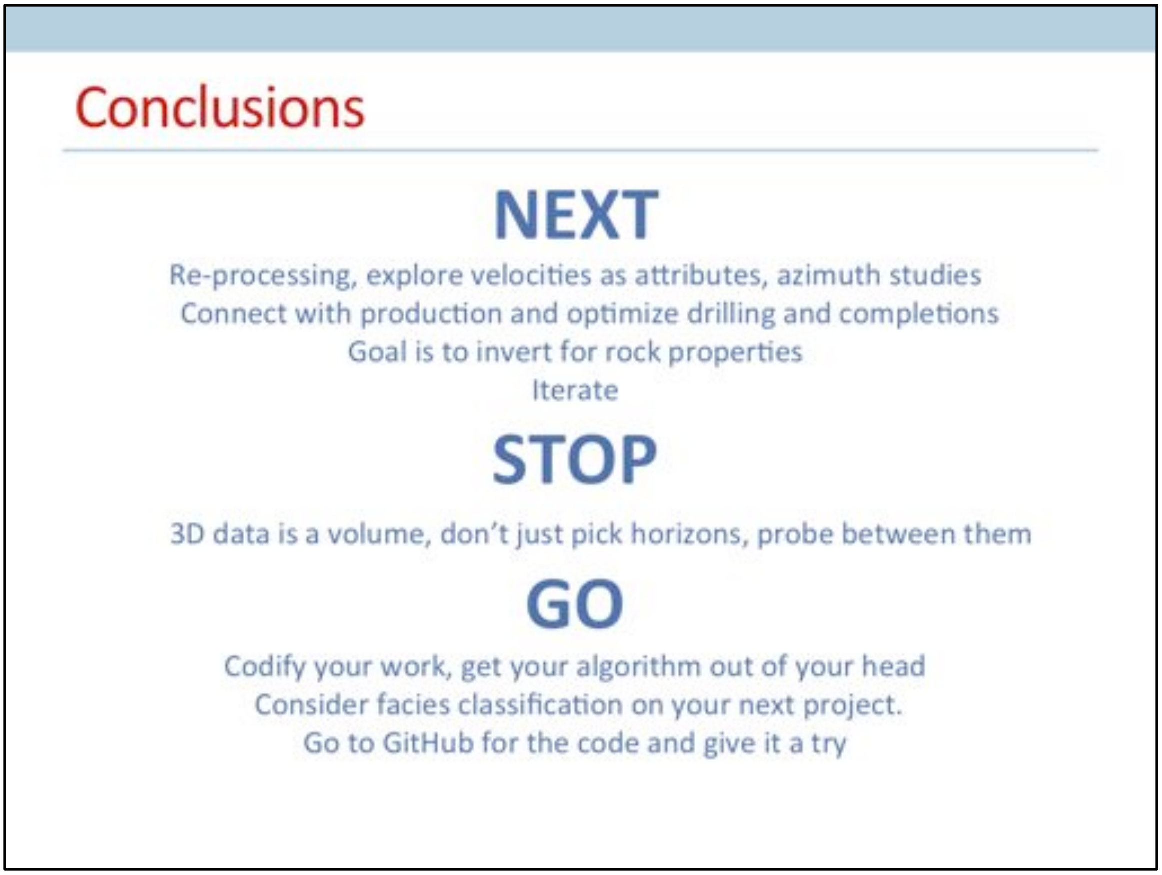
There are plenty of features to compare here, and once again the amplitudes, faults and form lines have been overlain to help your eye make comparisons. The diagenetic caps are very well represented in 3D version.

We could use a fold volume as yet another attribute to classify this region off into its own space. Essentially using another attribute as a filter.

The next slide shows a time slice at 1000 ms, at the horizontal green line.




I think this a mindset we need to embrace. Volume attributes are volumes. Even spatially irregular diagenetic cap rocks have a full expression in a volumetric sense. It is up to us to provide that to the rest of the subsurface workforce. So engineers can drill better wells, so geologists can make correlations when you hand over your work.



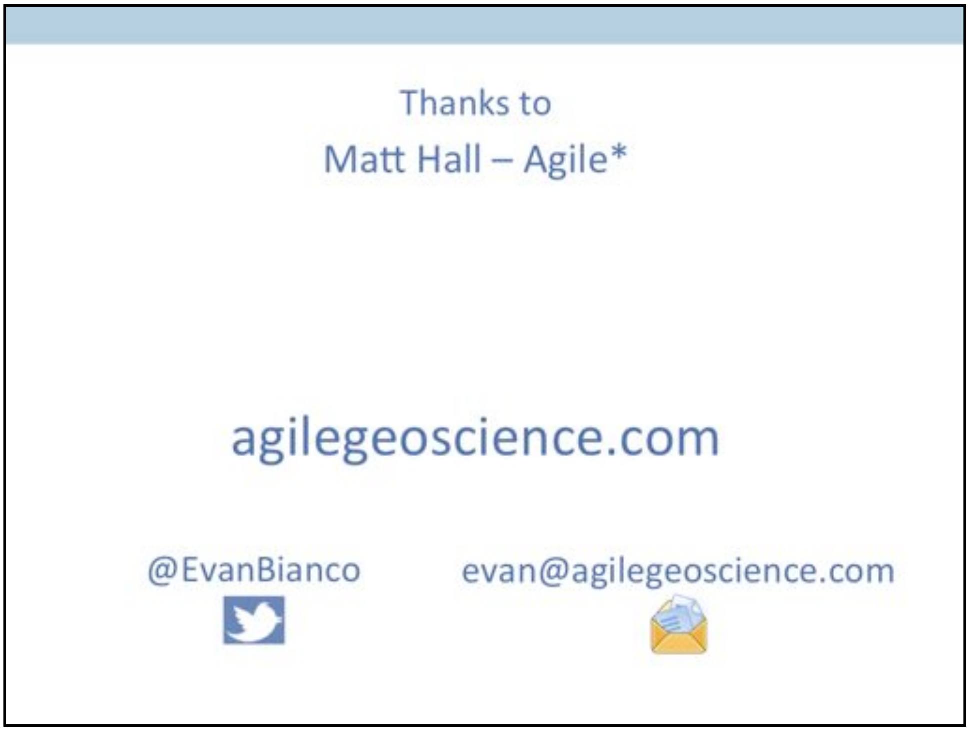

This is a demonstration of a comprehensive classification scheme stemming from a single input volume. Interpretation and insight were essential in honing the algorithm to describe the geology.

Some of the remaining work to be done includes a reprocessing of the volume (already underway), and a exploration of some of the prestack attributes, including processing velocities, and interval velocity volumes as attributes to include into this workflow. Shear wave processing is an option that may discriminate open vs closed fractures. The ultimate goal is to extend to rock properties and produce an algorithm that can be easily repeated if and when the inputs are change. We feel that the ability to iterate is the best way for subsurface characterization to stay relevant.

Stop yourself from making surfaces from data-rich 3D volumes. If you are picking reflection events, use them as boundaries to probe the pixels between them. And if you use this word “interpretation”, please preface it with what you actually mean. Better yet, discard it from your vocabulary altogether.

Things you can go and do:

1 Whenever possible see to make your interpretive work into an algorithm. Get that instinct and gut feel out of your head and into an algorithm. I think you will see that there is a new creative challenge in that process. New art.
2 Consider quantitative clustering and classification schemes for your next project and you can go to GitHub and try out my algorithm if you want to give it a try.
3 I’d be happy to help you test it out (It would be interesting to see it operating on more data sets than the collection of textures in my linen closest).




Thanks to the operators, who wish to be anonymous, for giving me permission to talk about this work, and to Matt at Agile for fruitful discussion and problem solving. You can reach me by email, on Twitter, or via our blog at agilegeoscience.com.