The Record

Denver Geophysical Society

Volume 51 - Number 1 - May 2026

Upcoming Events

May Luncheon
- May 14, 11:30 am @ Wynkoop Brewing

DGS/RMAG Rockies Game
- May 20, 2026

June Luncheon
- June 11, 11:30 am @ Wynkoop Brewing

URTeC 2026
- June 22 – 24
- George R. Brown Convention Ctr, Houston, TX

DGS Golf Tournament
- July 28, 2026 @ The Ranch Country Club, Westminster, CO

IMAGE 2026
- August 24 – 27
- George R. Brown Convention Ctr

CSM Geophysics 100th Anniversary Celebration
- September 18 – 19
- Colorado School of Mines, Golden, CO

Special Edition

3DSS 2026 Photo Wrap Up

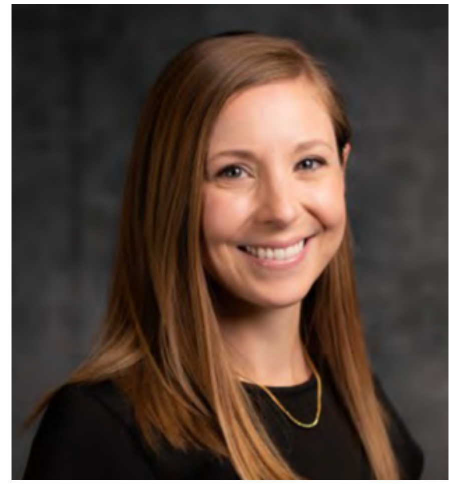
In This Issue

***(*) Editor's Note** - This issue features the first installment of a three-part series by Steven Clawson of GeoData2Knowledge, LLC, with parts 2 and 3 appearing in future issues. This article starts on page 21, with the full article continued on page 27*

Executive Corner

Jess Puyear

President,
Denver Geophysical Society



Happy Spring to the DGS!

I would like to thank the volunteers, speakers, vendor, and attendees of the 31st Annual 3D Seismic Symposium. Attendance numbers have steadily increased since covid years, and I know that can be directly attributed to the work put in by the committee and the quality of the talks given. We really appreciate all of the input for those attendees that filled out the survey. The committee has already met to discuss any ongoing improvements we can make to the symposium. Your voices are heard!

One thing I will address is that we remain committed to providing a diversity of geophysically focused talks and topics. If you are interested in seeing more of any particular topic, please submit a paper or encourage your colleagues, vendors, and peers to help support those topics. The more options the committee has, the more we can adjust our selections to what the crowd wants to hear. Operator talks focusing on case studies has risen to the top of the polls every time we survey, so if you are working for an operator- please consider a talk submission for next year.

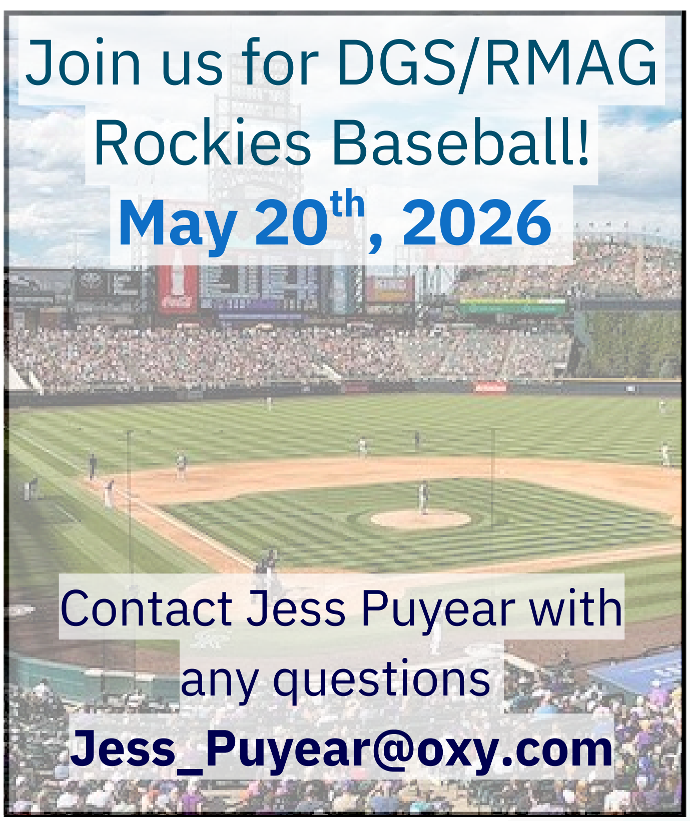
We are looking forward to the spring baseball game this year. We are changing it up a bit and will be sharing a suite with RMAG. This requires sponsorship but provides a broader networking opportunity and flexibility for weather. We really hope to see you there!

In the spirit of spring cleaning, we are cleaning out our storage facility! We will keep anything that looks to have value, but our need for a storage space is waning. There will likely be some items showing up in the silent auction at the holiday party that we no longer need. Please reach out if you'd like to help with the clean out!

We thank our 38 sponsors and 11 Exhibitors for supporting the 31st annual 3DSS Symposium! The 3DSS is the seminal geophysical annual event in the Rocky Mountain region and the support of our sponsors is critical to our success. We truly appreciate the 3DSS Committee and the Student Challenge Bowl Committee whose hard work and determination gave us the foundation for a great event!

Thank you to Dave Purcell

for his generous contribution of photos to this issue of The Record



Denver Geophysical Society

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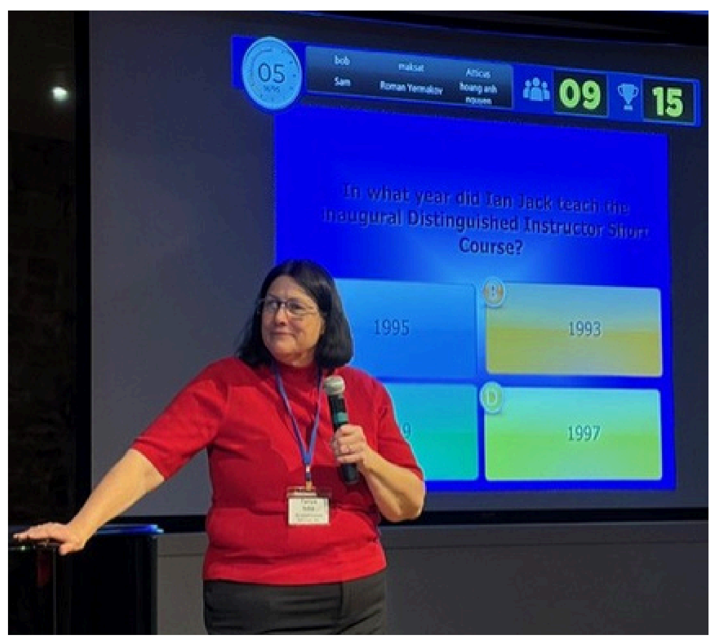
2026 DGS Student Challenge Bowl

Seven student teams from Colorado School of Mines, University of Colorado, Colorado State University, and University of Denver competed to correctly answer geological, geophysical, and SEG-related trivia questions with audience participation during the 3DSS Icebreaker on March 4th.

2026 DGS Student Challenge Bowl

Congratulations to Winners Maksat Jazbay and Bob Crummett (CSM Geophysics PhD students), and to CU student Atticus Baker and CSU grad student Sam Burton for taking second place!



Special shout out to Scott Cook for running the event, and thank you to all who competed, volunteered, and attended for making this year's Student Challenge Bowl a success!

2026 3DSS Technical Program
Morning Session

Session I - Chairs—Morgan Brown and Sissy Theisen

8:30 Opening Remarks

8:40 *Kickoff talk:*
Photons, Phantoms, and Agents: Microseismic Detection, Synthetic Data Generation, and Agentic Modeling
Bob Clapp, Google X

9:25 **What do we need for improved handling of the near surface and how can we get it?**
Christof Stork, Land Seismic Noise Specialists

9:50 Break

Session II - Chairs—Grace Bastianon and Jess Puyear

10:15 **High West CCS Project Design: Maximizing Storage, Minimizing Impact**
Brad Birkelo, BKV

10:40 **Higher Mode Amplitude Variation with Azimuth as a Fracture Fluid Indicator: A Pannonian Basin Geothermal Case Study**
Scott Cook, Tricon Geophysics

11:05 **Cascade Tomography Applied to Karsting in the Permian Basin**
Chuck Diggins, DigginsGeo, LLC

11:30 Lunch Break

2026 3DSS Technical Program
Afternoon Session

12:20	*Keynote Address:* **The Mechanics of Wastewater Injection and The Challenge of Containment from Basement to Surface** Seth Busetti, PhD Center for Injection and Seismicity Research (CISR), Bureau of Economic Geology
1:05	Break
	Session III—Chairs—Sarah Gach and Lisa D'Ambrosia
1:35	**Integrating Cross Discipline Data to Optimize Production and Prevent Casing Deformation in the Austin Chalk Play of South Texas** Jon Holt, Black Mountain Oil and Gas
2:00	**The role of 2D seismic data in the evaluation of the Goodland unconventional reservoir** Friso Brouwer, I^3 Geo
2:35	**Discovery and Development of the Corvinus Unconventional Gas Field, Hungary** Michael Peffer, Aspect Energy
3:00	Break
	Session IV—Chairs—Andrew Keene and Jeff Zawila
3:25	**Enhancing Frequency Content of Onshore Seismic Data with Advanced Bandwidth Extension** Marianne Rauch, Lumina
3:50	**An overview of modern 6C ultra high-density 2D multi-component seismic reflection program in the Northern Upper Mississippi Embayment, Western Kentucky** Ted Stieglitz, Explor
4:15	**Using the Wave-Equation Based AVO Inversion to identify Dolomitization within Carbonates: Canning Basin Case Study** Hansel Gonzalez, Autana Geoconsulting; formerly Delft Inversion
4:40	Closing Remarks - Best Speaker voting - Drinks & Awards

Kickoff Talk

Bob Clapp, Google X

Photons, Phantoms, and Agents:
Microseismic Detection,
Synthetic Data Generation, and
Agentic Modeling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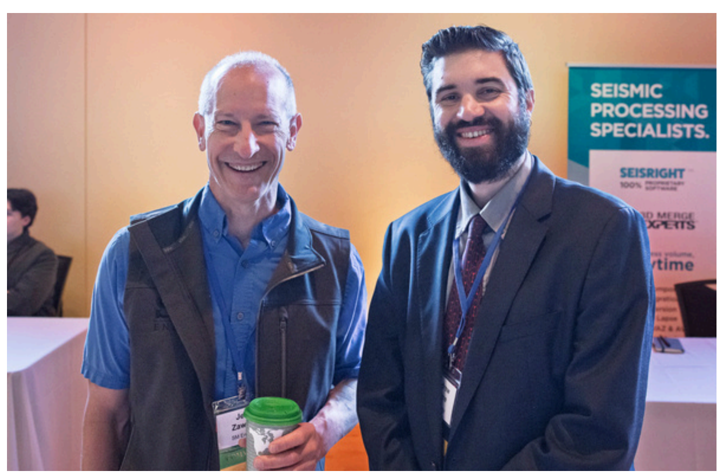
Seth Conway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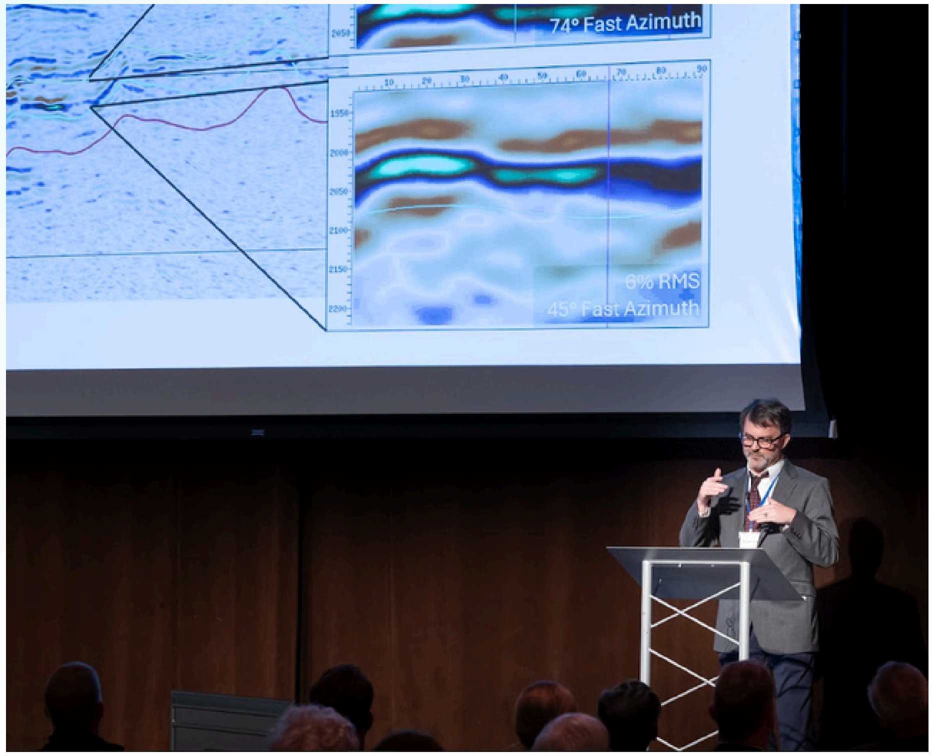
Morning Technical Session

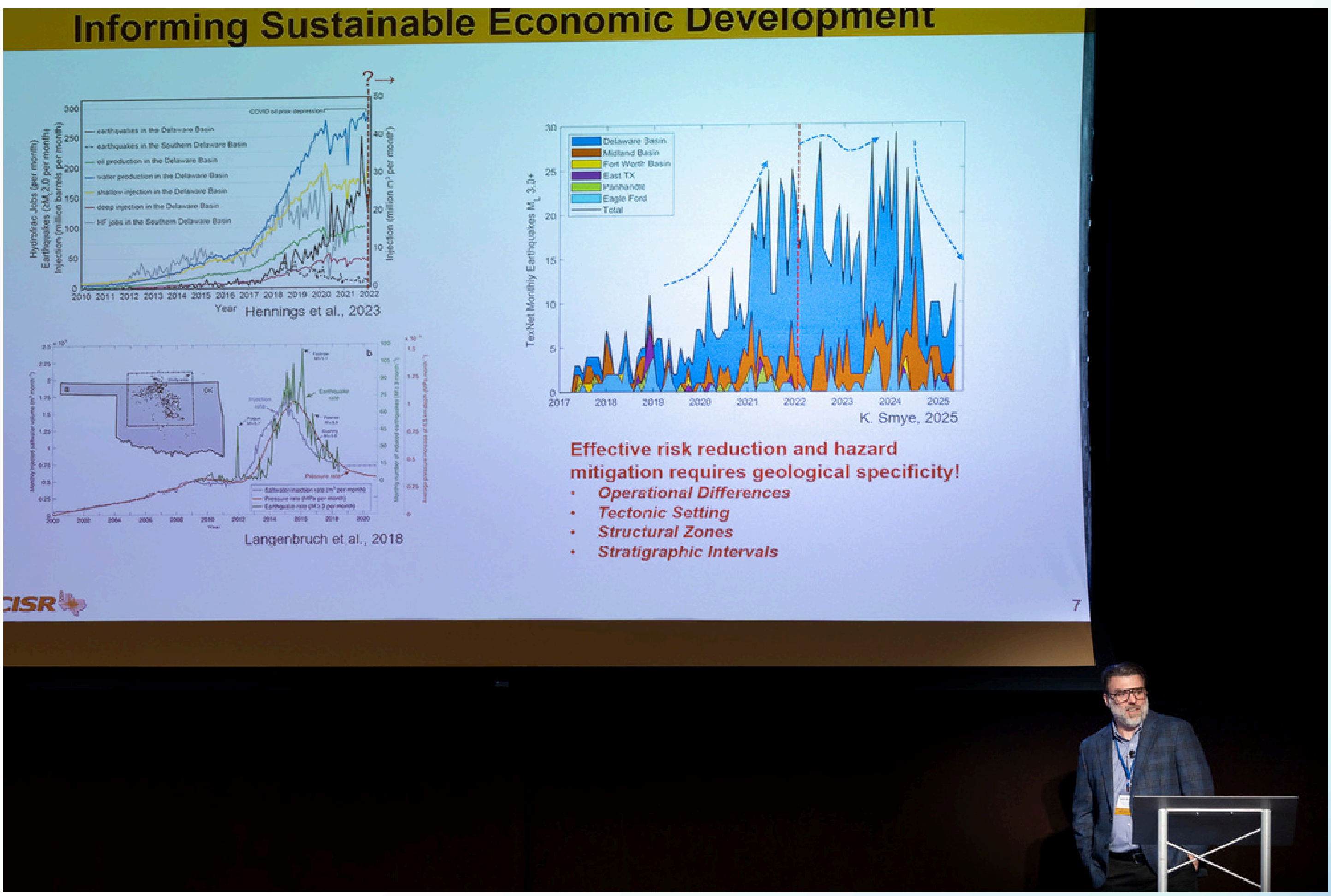

74° Fast Azimuth
6% RMS
45° Fast Azimuth

Keynote Address

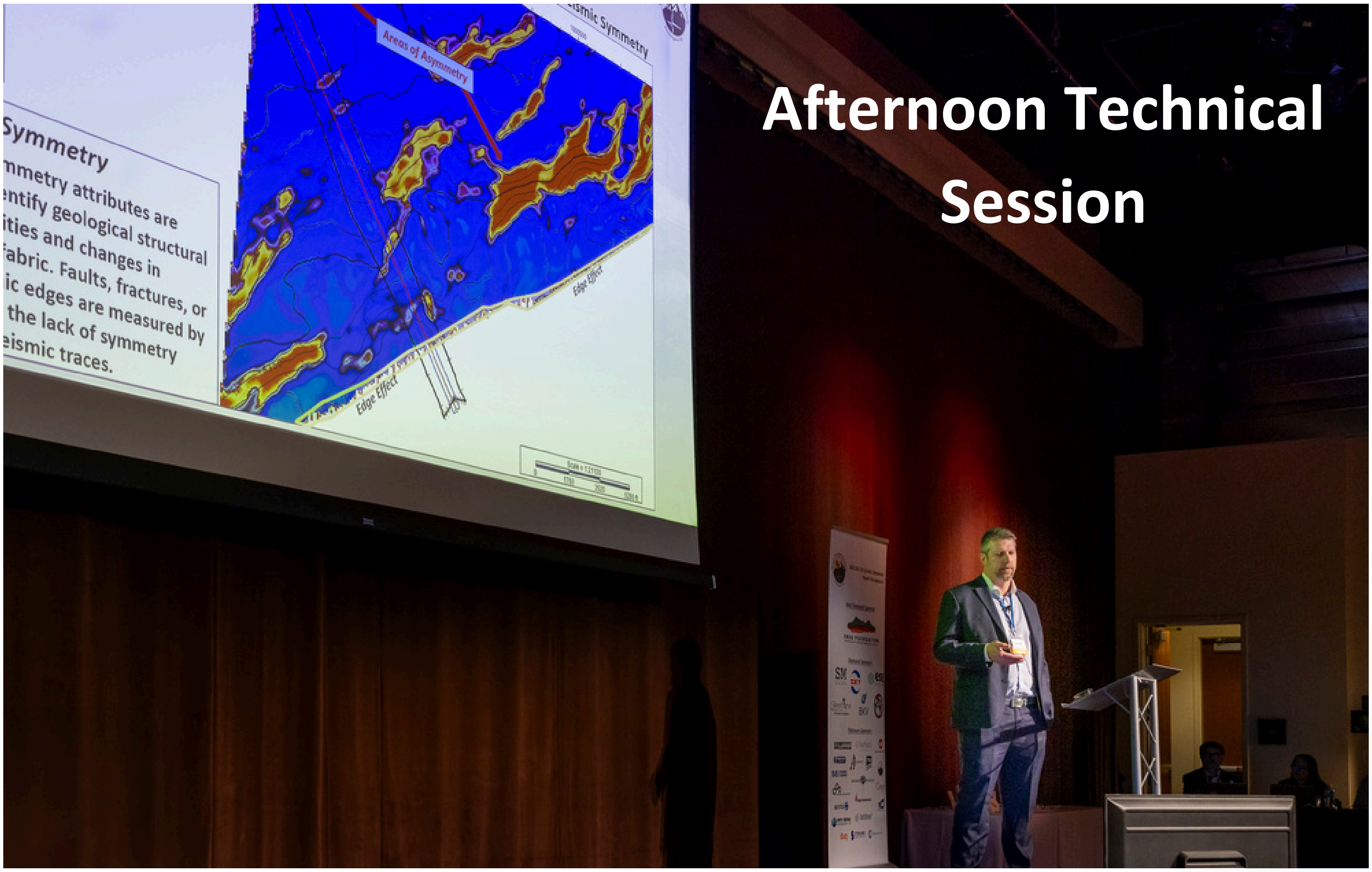
The Mechanics of Wastewater Injection and The Challenge of Containment from Basement to Surface

Seth Busetti

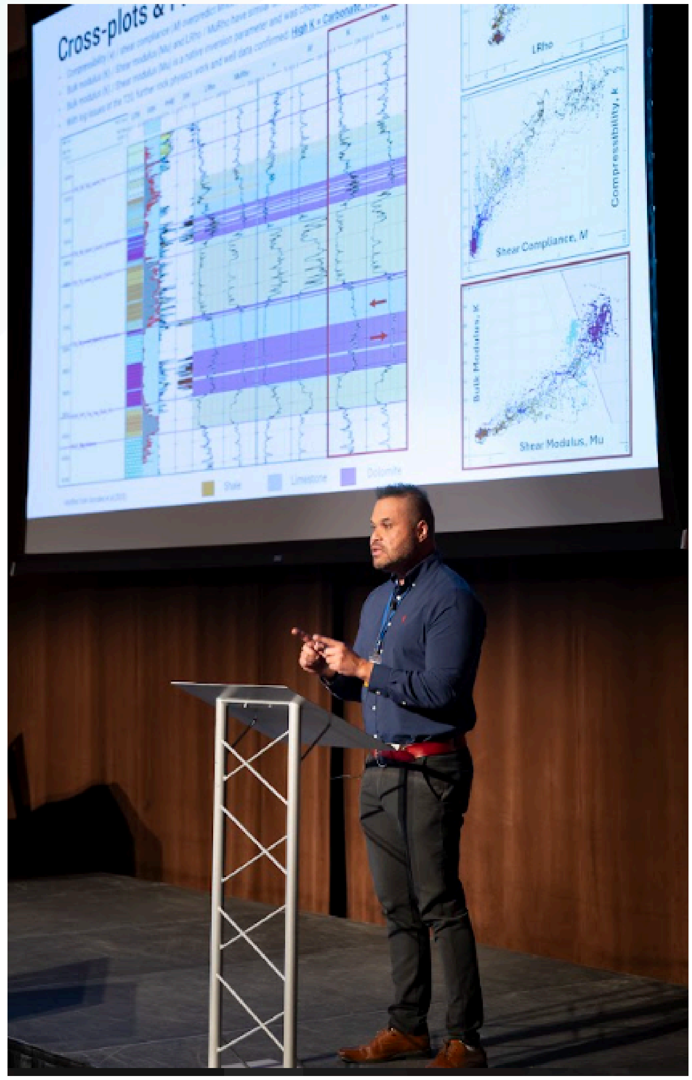
Center for Injection and Seismicity Research (CISR), Bureau of Economic Geology



Afternoon Technical Session




The Leading Light in Energy


Compressibility, k
Shear Compliance, M
Shear Modulus, Mu


An overview of a modern 6C ultra high-
component seismic reflection program in the Northern
Mississippi Embayment, Western Kentucky
T. Stieglitz*, D. Laymon, B. Doll, Collier Geophysics
E. Woolery, S. Hampson and K. Woller, Univ of Ky Dept of E&ES
A. Chatenay, Explor
(* now at Explor)

DGS 3DSS — Exhibitors

Earth Signal Processing, Inc

Allstate Permit Services

Microseismic

Vantage Geophysical Corp

Paragon Geophysical Services

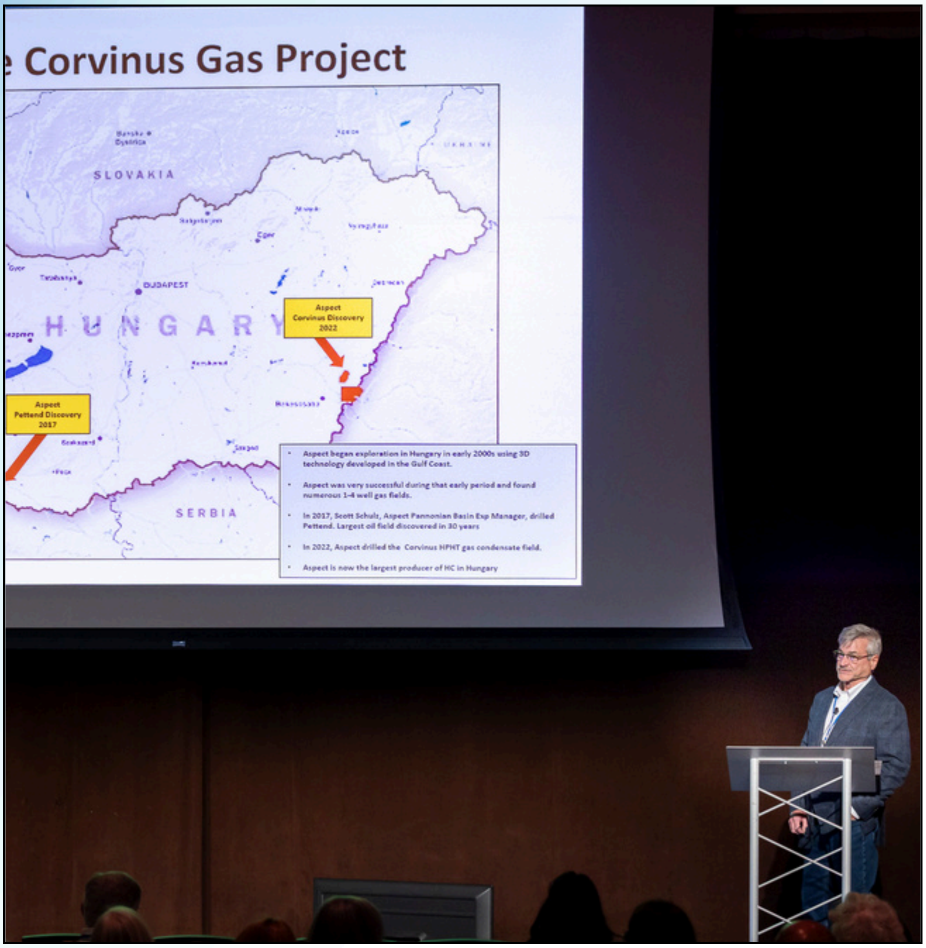
Telemark Energy Services

Exhibitors not pictured:

GeoComputing Group, GeoSoftware, Silverthorne Seismic LLC, Echo Seismic Ltd, Qeye

Volunteers Extraordinaire

Thank You!



R. Randy Ray
Best Speaker Award
Mike Peffer, Aspect Energy

Discovery and Development of the Corvinus Unconventional Gas Field, Hungary

DGS Philanthropies — Scholarships

In 2025, DGS introduced $2,500 scholarships to be awarded to students in Colorado doing geophysical work at university.

To be considered for the scholarship, please send an email to excom@denvergeo.org with the following information:

1. **Name and School**
2. **Expected graduation date**
3. **Geophysical project/thesis/work (paragraph)**
4. **Why you need $2,500**
5. **Future career goals**

The deadline for applications is June 30th, and scholarships will be awarded in July. We will be visiting campuses to help promote the scholarships and answer any questions, events TBD. Once awarded, the student must commit to sharing the relevant work at a monthly DGS luncheon in Denver.

We are very excited to be able to offer these funds to students as a way of supporting our local community and keeping Denver-area geophysics strong and thriving well into the future! For any questions, please contact Andrew at akeene@sm-energy.com or Jess at jess_puyear@oxy.com.

https://denvergeo.org/events/2025-dgs-scholarship-program/

DGS 2026 Golf Tournament

Tuesday, July 28th

The Ranch Country Club,
Westminster, CO

Quantifying the Unknown: Uncertainty Estimation in Prospect Evaluation - Part 1

by Steven Clawson, GeoData2Knowledge, LLC

Introduction

Current prospect evaluation methods rely on qualitative and "gut feel" attempts to measure the chance of success of drilling a prospect. I will illustrate the need for and means to better analyse risk in regards to the upstream oil and gas industry, focussed on conventional plays. Specifically examining the use of seismic data to predict reservoir characteristics, porosity, fluid type, sourcing, and sealing capacity, along with an associated uncertainty estimation for risk analysis. I hope to pass on a few ideas and learnings gathered over a long career. And a plea to modernize prospect risk analysis. This is not the solution, but instead highlights better ways to go about the process.

Risk analysis, or Chance of Success (COS), is key to evaluating if a prospect is economically viable or not and classically uses probabilities where it is assumed that you can put a number on each of several elements that make up a successful prospect outcome. Many ad hoc methods are used in this regard. Instead of strictly probability outcomes, I'll focus more on the general term of uncertainty estimation which relates to what you do and don't know. Handling uncertainty is a balance of being bold and being reckless. This gets to questions of quality of data, such as how good are those seismic data, how valid are the well log data, what does that pressure test tell me. The key thesis is to integrate data into prospect risk analysis using a Bayesian approach, allowing new information to dynamically update the risk assessment. And by data, this comprises whatever knowledge you can gain towards the risk assessment. I'll be focussing on 3D seismic data.

Prospect evaluation is a vast topic, and the application of any method is heavily influenced by specific particulars, including the available data and whether the analysis is for exploration, exploitation, or a single well evaluation. Given the extent of the subject, doing it justice would take more writing than this series can handle. My opinions are biased attempt to sync these ideas together over the coming year.

Prospect evaluation is fundamentally tied to economic viability. And uncertainty estimation constitutes a major part of that evaluation. While a simple economic criterion like the Present Value Multiple (PVM, equivalent to DROI+1) can be effective, optimizing your percentage of an opportunity's investment can be highly beneficial. The Kelly Criterion offers an interesting methodology to optimize this investment percentage relative to its risk (an intriguing way of looking at risk outcomes you might want to search on your own). For simplicity, a working interest percentage equal to the risk percentage is a robust way to proceed, assuming the investor operates within a broad portfolio of opportunities.

A cautionary example of a major industry flaw: when a prospect's predicted value is so large that any "reasonable" risk value still makes drilling appear economic, leading to a "too big to fail" scenario. But then it does. The industry needs better ways to handle this issue. Later in this series the concept of failure modes will be addressed. And how do you handle black swan events? In the end there is always irreducible risk. Relying on conservative quantitative risk assessments, I claim, is the way to long term success.

Historical Look at Prospect Risk Analysis

Classic Prospect Risk Analysis is often based on intuition and experience. Simplistic 3-component models (area of accumulation, average net pay, and HC recovery yield) are often used, but tend to be overconfident in the final Chance of Success (COS) estimate. A better approach uses five components:

- Hydrocarbon Charge (source rocks, basin thermal history)
- Migration and Timing of HCs (pathways, distance, shadows, when)
- Reservoir Presence (lithology, porosity, thickness)
- Trap (stratigraphic or structural)
- Containment (sealing capacity, preservation)

Where each of these components are made up of several underlying sub-topics. And the typical assumption of each being independent is problematic.

A critical issue in classic analysis is that these probabilities of each component are multiplied together to calculate the COS. This multiplication drastically lowers the final COS, leading to subjective "fudges" to boost the probability to a value that "feels right". Furthermore, in a multi-targeted prospect, assuming independent targets can lead to an overly optimistic assessment. Each of these 5 major components consist of subjective sub-step components (e.g. migration and timing incorporates: fetch area, migration distance, pathways, shadowing, and trap timing). How to compile these individual pieces of information into a single factor is subjective.

Setting these classical risk factors generally use rubrics such as:

- Low chance: 10% - 30% COS
- Fairly unlikely: 25% - 40% COS
- Coin toss: 50% COS
- Reasonable confidence: 60% - 80% COS
- Virtual certainty: 90% - 100% COS

Using 100% is reasonable if all necessary information for a particular component is known. Conversely, a lack of data does not equate to zero chance, as "absence of evidence is not evidence of absence".

More data is beneficial to a better evaluation and quality of the risk factor, either better or worse. And interpretations continuously improve in quality with added data. As part of portfolio management, it is important to track the critical chance factors for a given play to guide data acquisition (value of data methods) and calibrate the predicted COS over time. But because the oil industry is capital-intensive and most entities lack access to large amounts of proprietary information, industry consortiums often compile well data and other pertinent data to gain meaningful information, though consistency in this compilation remains a concern. It is almost always the case that the interpreter never has all the information necessary to make the optimal evaluation. So using all the information that you have in an integrated way, trying multiple hypotheses, and making all aspects of the information self-consistent with the interpretation is the goal.

As said previously, it is the economics that are most critical and that leads to what measure of predicted volumetrics of the prospect is being evaluated. And again there are many ways in which volumetrics are estimated. Ideally with 3D seismic data and modern software you start with a gross rock volume. Then cut that with measures of: net/gross, porosity, water saturation, recovery percentage and hydrocarbon properties. And since all of these measures should be thought of as uncertainty distributions, when taken together, are estimated as log normal distributions due to the multiplication of several normal distributions together. This raises questions about which risk value (COS) to apply to which volumetric distribution value (P99, P90, or P10 volumetric outcome).

Typically the P99 volume (the smallest, but most likely to succeed) is given the COS called Pg and noted as “getting on the curve”, or graph, of the lognormal distribution. But then what is the COS of getting the P90 or P10 volumetric outcome?

A common pitfall is the reliance on a single geological model along with many unquestioned assumptions. Experience and local geologic information is essential for estimating COS. Sometimes, however, enough of a story is sufficient to cause a prospect to be drilled, allowing for learning as the project progresses. Serendipity is great, take it every time. Learning from dry holes and conducting post-mortems is essential for providing feedback and calibrating the overall risk assessment of a play.

As you can see, this is a broad topic and optimal workflows must adjust to the immediate needs at hand.

A Philosophy for a Better Method

Prospecting methods exist on a spectrum, from simple time maps and relative amplitude maps to detailed Quantitative Interpretation (QI) using advanced software. The principle of “Fit for Purpose” is essential, requiring efficient workflows that utilize the data and integrate the 3
information available. Avoid over-fitting the data and predicting beyond what the data can give you.

I advocate using a pseudo-Quantitative Interpretation approach (pQI). Obtaining absolute rock properties from seismic data using a full QI approach is fundamentally limited by high uncertainty and non-uniqueness, and typically takes too long. Although these technologies are valuable, mastering the fundamentals is more critical. These fundamentals can be assessed using first principles (guided by physics, chemistry, and geometry) and analogs (visual and data science methods). A major concern is that paradigms can cause "myopic thinking". Complex geology and data issues mean that unforeseen outcomes are always possible. Mother Nature has a way of showing you something new when you didn't expect it.

Given the bias inherent in multiplying chance factors, a Bayesian information type of system is preferred. In this framework, data available for each risk component of a prospect evaluation adds information, which can move the resulting COS (posterior probability) up or down / better or worse.

The proposed Bayesian methodology is sufficiently flexible to accommodate many of these complexities. As an example of how a Bayesian methodology might apply to a seismic amplitude play: if an anomaly is shown to be greater than some background amplitude, this may appear interesting ("accurate" in terms of a testing procedure), but it is not necessarily predictive due to the existence of false positives in the area. This is known as the testing paradox. This risk analysis can be framed similarly to how a medical test predicts a patient's disease, where new information updates the understanding of the outcome. This process needs some sort of quantitative information to be added to the system in order to update the conditional probabilities for a COS estimate. More on this approach later in this series.

In order to add numerical information to this Bayesian analysis I'll get into quantitative interpretation methods where I'll focus on using 3D seismic data that provides geological understanding for an intelligent risk analysis method. While true Quantitative Interpretation (QI) methods are great in predicting detailed information on a prospect, they are detailed and time-consuming, making the pseudo-quantitative approach (pQI) more practical unless a full reservoir model for simulation is required (for example). Critically, the inherent uncertainties in prediction when using quantitative methods must be kept in mind.

Full article continued on page 27

May Luncheon

Mapping serpentinization in geologic hydrogen systems using magnetotelluric phase tensor

Dr. Biruk Abera Cherkose
Postdoctoral Fellow, Center for Geophysics, Energy, and Minerals (CGEM), Colorado School of Mines

Geologic hydrogen has attracted increasing attention in recent years from both academia and the energy industry as a promising emerging energy resource. Among the different mechanisms proposed for its generation, one of the most important is the serpentinization of ultramafic rocks, a water-rock reaction in which hot fluids interact with Fe-rich minerals.

Conventional geophysical approaches for identifying serpentinization typically focus on changes in bulk physical properties. However, serpentinization is not only a bulk alteration process. These processes generate electrical anisotropy, which contains information about rock fabric and alteration geometry that may not be fully captured by isotropic bulk-property analysis alone.

In this presentation, we investigate the use of magnetotelluric (MT) phase tensor analysis as a means of detecting electrical anisotropy associated with serpentinization.

Our results show that phase tensor analysis can provide a valuable additional perspective for detecting serpentinization-related anisotropy in potential geologic hydrogen source rocks. This expands the geophysical toolkit available for geologic hydrogen exploration by moving beyond bulk-property detection toward the identification of directionally organized conductive fabrics linked to alteration processes. In this sense, the proposed approach offers not only a method for recognizing serpentinized zones, but also a framework for better understanding the structural and physical architecture of hydrogen-generating systems.

Speaker Bio

Dr. Cherkose obtained PhD degree in Geosciences from the UAE University, Master degree from Kyushu University in Japan in the field of Earth Resources Engineering. In the Geological Survey of Ethiopia, Dr. Cherkose has contributed to geothermal exploration as an exploration geophysicist. Dr. Cherkose investigated subsurface structures of the Semail Ophiolite in the UAE, with emphasis on ophiolite obduction processes and foreland basin formation. Currently, Dr. Cherkose's research focuses on geologic hydrogen exploration, particularly using magnetotelluric methods to map serpentinization in mafic and ultramafic rocks that may serve as source rocks in natural hydrogen systems.

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Information for Contributors

Your editorial contributions are encouraged, particularly about classes, seminars, personnel news, company news, or other items of interest to the geophysical community. All suggestions and manuscripts should be emailed to DGS at office@denvergeo.org. Targeted deadline for submissions is the first of the publication month (February, May, August, November) but exceptions can be made with the editor's approval. We reserve the right to edit all material according to standard practices.

Opinions expressed within are solely those of the authors. They are not to be interpreted as those of the DGS.

Keep it Professional

Do you have news you would like to share with the community? A job change or a new promotion? Anything that's industry/job related, we would love to share your news. For consistency, DGS reserves the right to edit and limit what gets published.

Technical Discussions

DGS would like to share Technical Discussions on topics of interest to our community. Please submit short papers to office@denvergeo.org for consideration. DGS reserves the right to edit and limit what gets published.

About DGS

The Denver Geophysical Society (DGS), a chapter of the Society of Exploration Geophysicists (SEG), was chartered in 1950 and has been an active part of the Rocky Mountain region geophysical community for 72 years. Starting in 1995, DGS added the 3D Seismic Symposium to its annual programming.

Mission Statement: The Denver Geophysical Society is a nonprofit organization operated by its members to promote the science of geophysics, especially as it applies to exploration, and to promote fellowship and cooperation among those persons interested in geophysical problems.

By Laws: The Denver Geophysical Society 2010 Executive Committee updated the By Laws. To review the updated By Laws, visit the By Laws subtab on the DGS website.

Committees: The Denver Geophysical Society is mainly comprised of volunteers that help plan the continuing education courses, monthly luncheons, golf tournament, networking events, student outreach programs and so much more! To learn more about the committees and available volunteer opportunities, email office@denvergeo.org.

Officers: The officers are elected volunteers that are an integral part of the governing and planning of the Denver Geophysical Society. Officer terms are dependent upon the position held and range from 1 year to 4 years. If you are interested in running for an officer position, please email office@denvergeo.org.

Privacy Policy: At The Denver Geophysical Society (DGS), a chapter of the Society of Exploration Geophysicists (SEG), we are committed to protecting your privacy. We use the information we collect about you to provide member services, process orders, provide on-going support and supply membership announcements.

Denver Geophysical Society
www.denvergeo.org

Continued from Page 24

Quantitative Interpretation (QI)

Since most of my career has been focussed on Quantitative Interpretation (QI) I'll lay out how I approach this and how to influence the Prospect Risk Evaluation.

Figure 1 illustrates what information is available from seismic data:

1. **Structural Framework**: Horizons and faults (requires time-to-depth conversion).
2. **Stratigraphic Gridding**: Sequence boundaries, stratal-slices and Wheeler diagrams showing expected sedimentological systems.
3. **Lithology and Facies**: Sedimentological morphologies (from stratal slices of inversion attributes, spectral decomp, RGB maps and machine learning).
4. **Pressure Field**: Pore pressure changes (by velocities and over-pressured signatures of attenuation on seismic).
5. **Rock Properties**: Amplitude anomalies, AVO, DHI (from inversion, and machine learning).
6. **Fault & Fracture Networks**: Interpreted fault cuts, juxtaposition situation (fault likelihood detection, subtle structural changes, and pattern recognition & textural algorithms).
7. **Reservoir Fluids & Dynamic Response**: AVO, DHI (from application of rock physics modeling, down-dip conformance, flat spots and time-lapse seismic).

Figure 2 relates a 1) stratigraphic layered section to, 2) well logs of various measurements, 3) a resulting impedance layered section, as the seismic data responds to impedance changes, shown in 4) as the reflectivity, then convolving a wavelet onto this reflectivity produces a synthetic seismogram in 5), that can then be related to actual seismic data as in 6).

Figure 1

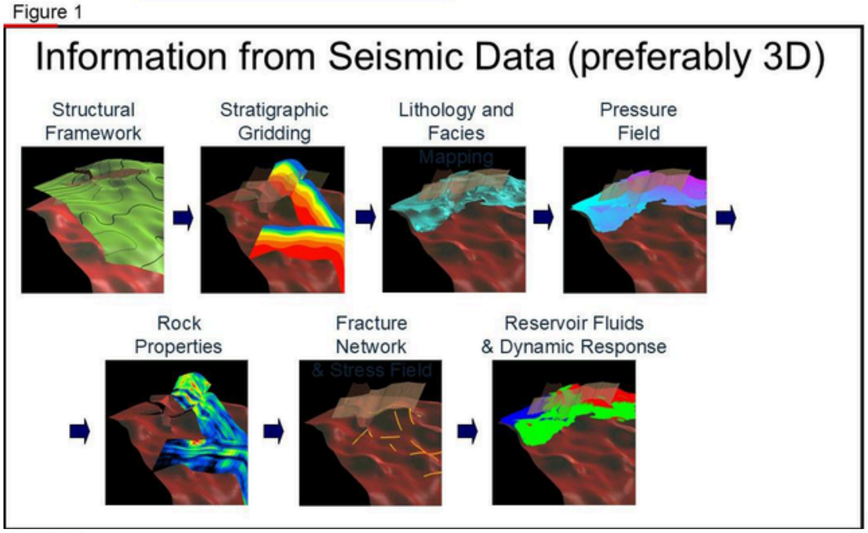


Figure 2

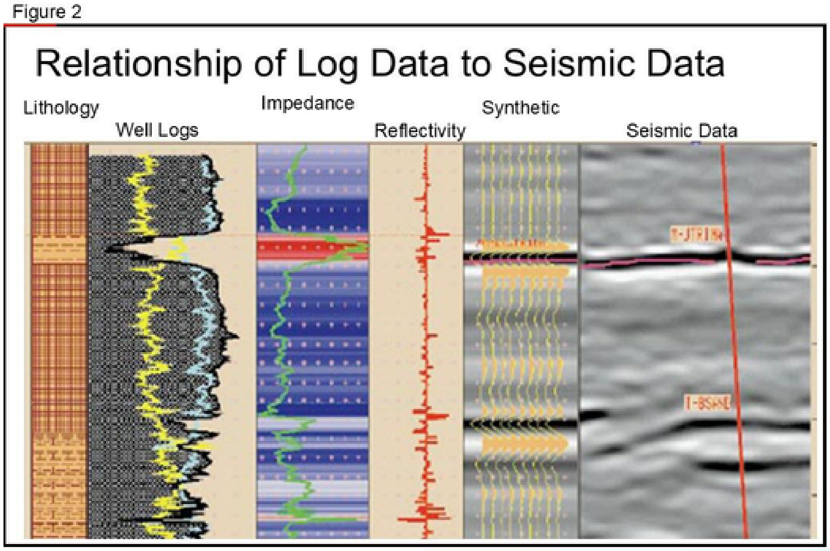
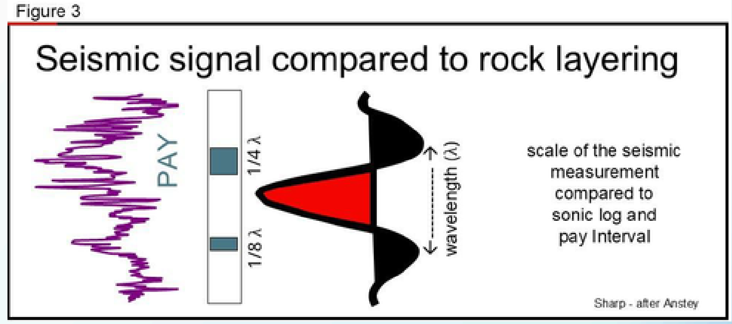


Figure 3 reminds us of how large the seismic wavelet is relative to typical geologic stacking patterns. This bandlimited wavelet vertically averages the properties in an effective medium way. Vertical resolution requires seismic events to be separated by more than half the wavelength, which is actually a very rare occurrence. How does the seismic response relate to the predictability of rock properties when they are mixed together by this wavelet? Tuning is a big issue that is also very complex to understand.

Figure 3



Since the wavelength of the wavelet is important to know in estimating what the observed data is encoding of geologic information then additional parameters are needed. The phase of the wavelet needs to be found. Since a causal elastic wavelet is propagating through the earth, taking the form of a minimum phase wavelet, the data needs to be deconvolved. This resulting wavelet, after the many assumptions in the deconvolution, is not necessarily zero-phase though. As long as the seismic processing makes the wavelet stable temporally and spatially then you can further refine the data to be zero-phased by means of a phase rotation or preferably by wavelet deconvolution.

Zero-phased data gives you the highest resolution of any equivalent bandlimited version of the wavelet. Next this temporal wavelet needs to be converted to depth to get the wavelength measure, it will vary in length due to velocity changes throughout the seismic interval. Simple methods associate the dominant frequency of the data with determining the wavelet length by: λ = Vint / Fdom. But if your data are spectrally flat then the dominant frequency no longer represents what is needed. A statistical wavelet only measures the bandlimited nature of the data and then imposes a zero-phased outcome to the modeled wavelet. You could measure a wave period from this statistical wavelet, if you have corrected for the more egregious phase variations, and use that to measure the wavelength: λ = Vint * period / 2. And an extracted wavelet would give a more accurate portrayal of the actual wavelet in the data, if done correctly. Using the results of a single well-tie can be erratic. It's always better to take an average of several well-ties.

Since vertical resolution is where the seismic events are separated by greater than ½ of this wavelength, as a unit thins down to 1/4 λ, this is the tuning thickness, the seismic amplitude is affected while the isochron decreases. Commonly the brightest amplitude on the map is at that thickness of maximum tuning. Thicker (resolved) units may be a dimmer amplitude. While continued thinning down to 1/8 λ strongly affects the amplitude while the isochron remains nearly constant. This 1/8 λ is detection, as the information can still be used to some degree in discerning the geology. It just gets more uncertain.

When multiple events interfere within the seismic wavelength, the encoding of reflectivity becomes more complex due to constructive and destructive interference. To integrate seismic and well data, with their vast difference in scale, it is useful to upscale the log data (Backus averaging), integrate well ties, extract the wavelets, and perform wavelet deconvolution to produce the most geologically consistent zero-phased data. This zero-phasing is also crucial when using AVO methods to obtain the statistical fits of Intercept and Gradient measurements.

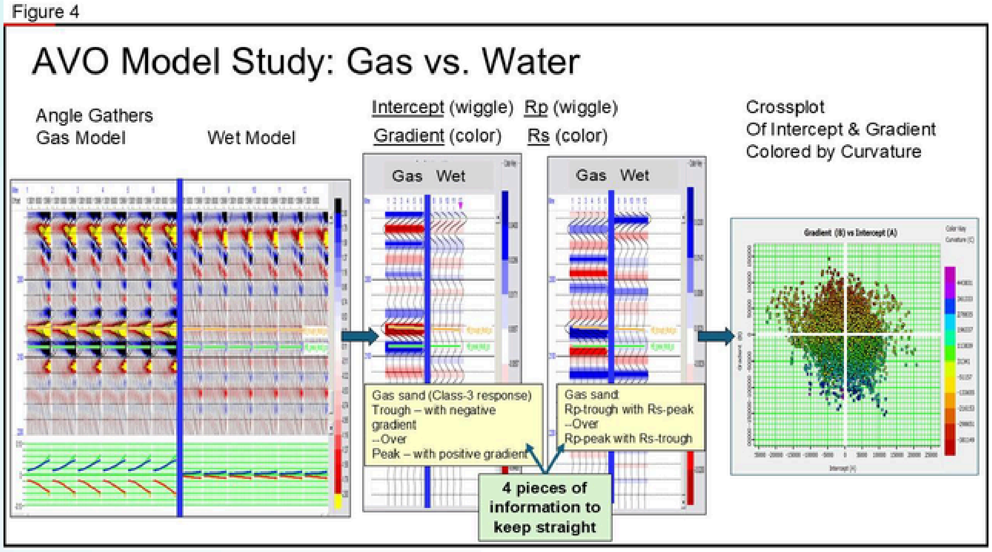
Furthermore, watch out for the wavelet side-lobes. Strong side-lobes, that negative amplitude on either side of the central positive part, imparts a stronger tuning effect in the data. I prefer to shape the wavelet in the data to have one octave slope on the low end and high end of the frequency band. Some practitioners use two octaves. Having a sharp cutoff in the frequency domain is not desired, and spectral bluing can be problematic if pushed to far.

Seismic Inversion converts seismic reflections (from impedance contrasts) into more geologically representative layer properties. It attempts to improve on the wavelet smoothing over the geology by an earth model that produces a synthetic seismic output equivalent to the observed seismic data, minimizing the mathematical difference. Inversion also provides data reduction (Top and Base reflections are converted to a single bed's properties). AVO effects can be transformed into properties like Acoustic Impedance (AI), Shear Impedance (SI), Vp/Vs, Poisson's Ratio (PR), and Density. It will not totally remove the wavelet, but it is moving in the right direction.

Figure 4 shows a modeling study of predicting reservoir rock properties using AVO (Amplitude Variation with Offset, sometimes called AVA for Angle Gathers, I'll stay with the term AVO). AVO is a major element of Direct Hydrocarbon Indicators (DHI). Seismic inversion is then used to obtain Acoustic Impedance (AI), Shear Impedance (SI), Vp/Vs, Poisson's Ratio (PR) and possibly Density from high angle raypath data. Azimuthal variations of AVO can also be used to predict fracturing and small scale faulting.

In this modeling study from well log data, a low impedance gas sand is layered within a shaley interval with the resulting angle gather on the far left showing a large increase in amplitude from near to far angles. By fluid replacement modeling of this sand to be wet shows the resulting angle gather labeled wet model, with hardly any reflectivity. Various AVO attributes can be derived from these angle gathers. The middle tracks show the Intercept and Gradient from statistical fits to the angle gathers using the Aki-Richards method for the gas sand and wet sand side by side.

Figure 4



Alternatively using the Fatti method you can derive the p-wave reflectivity (Rp) and s-wave reflectivity (Rs). This gas sand is seen to have a top reflection with a strong Intercept trough with a strong negative Gradient, a strong Rp trough (essential equivalent to the Intercept) along with a large positive Rs, due to the low Poisson's Ratio of this gas sand. At the base of sand these attributes are reversed: strong Intercept and Rp peak, strong positive Gradient, strong negative Rs. You can also measure a 3rd term to the angle gather called Curvature for angles above about 30 degrees. Typically land seismic data is not reliable at these high angles, but if you can measure it reliably it can help assess the density of the layers (useful for predicting porosity and if you have an LSG situation). So at most you have 6 pieces of information for each amplitude anomaly if the data supports it. Typically though, you will likely have the 4 pieces of information for each amplitude anomaly: top and base, intercept and gradient.

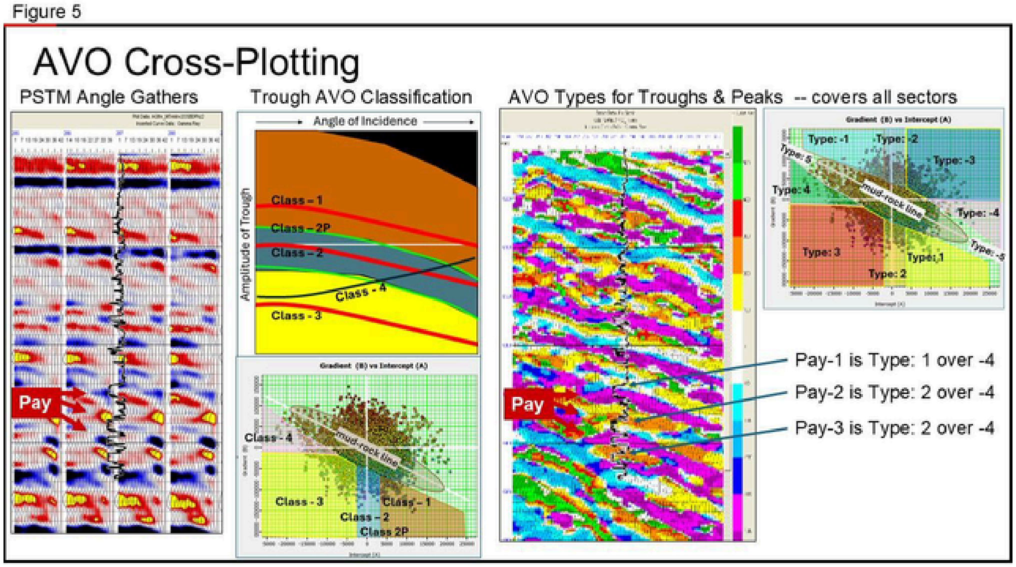
Be cognizant that at the step of taking the processed seismic gather and statistically fitting a curve for the intercept and gradient (and curvature?) is moving from a time series problem in normal time processing, where sampling and Nyquist frequency are important, to representing a waveform fine enough with evenly sampled points. It's better to over sample the waveforms for the statistics than what was needed in a normal time processing workflow. 3ms sampling works well for most situations.

The right hand side of Figure 4 shows an Intercept versus Gradient crossplot, colored by the 3rd term Curvature. The samples in this plot are for background and the gas sand and no trend is seen using this mixed set of seismic samples. It's where a particular sample point plots, relative to this classification scheme, that is informative.

The AVO attributes from Aki-Richards versus Fatti are related as follows:

- Intercept ~ Rp
- Intercept + Gradient = Scaled Poisson's Ratio Reflectivity (SPRC)
- Intercept - Gradient = Scaled Shear Reflectivity (Rs)
- Intercept - Curvature = Scaled Density Reflectivity

Figure 5



For communication it is often useful to classify these signatures. The most common form is the 1989 Rutherford and Williams chart which uses the Class-1, Class-2, Class-3 and Class-4 system. This is generally specified for the onset event of a trough/peak pair. Since seismic reflections are due to rock property contrasts between layers these classes are related to the following contrasts for the top event.

● Shale-on-shale reflections are the mud-rock line (typically referring to soft rock basins). These are essentially small peaks or troughs that dim with angle and represent the vast majority of the reflection on a seismic gather. This can be used as a background trend where a typical value should decrease in amplitude with angle at about -2dB (rule of thumb).

● Class-1: Intercept=peak, Gradient=negative, dims with angle. Contrast is a lower AI above higher AI below along with a higher PR above and lower PR below.

● Class-2: Intercept=small-peak / 0 amp / small-trough, Gradient=negative, trough increasingly negative with angle. This covers a narrow band of AI contrasts with 2 distinct looks. A Class-2p is a small peak event on the Intercept caused by a lower AI to slightly higher AI below. While the classic Class-2 is a near zero amplitude to small trough event on the Intercept. And in both cases a higher PR above to lower PR below. This negative gradient causes the Class-2p to change phase from a peak to a trough. And in both cases the trough gets more negative with higher angle. On a full stack of a CDP this can result in a very weak amplitude event. By understanding the AVO character you can predict the lithology of the geologic layers.

● Class-3: Intercept=trough, Gradient=negative, brightens, more negative, with angle. Contrast is a higher AI above to lower AI below along with a higher PR above to lower PR below. This is the classic “Bright Spot”.

● Class-4: Intercept=trough, Gradient=positive, dims with angle. Near angles are similar to a Class-3, but then the trough decreases amplitude with angle. Contrast is a higher AI above and lower AI below along with a lower PR above to higher PR below.

Notice that for Classes 1, 2 and 3 the gradient is negative no matter the intercept being a peak or a trough. This is due to the high-PR over lower-PR situation in these cases. These contrast combinations of AI and PR can be associated with certain lithologies, rock and fluid properties. Quartz is the one common sedimentary mineral that can have a very low PR while also having a wide range of AI values. Clays, coals and lignites typically have a very high PR. Classes 1, 2 and 3 have varying AI contrasts that could be shale over sand of varying porosity, fluid saturations or shales of varying hardness (pressure dependent). And the higher PR over lower PR is consistent with a shale over sand. Class-4 with the implied lower AI and higher PR is more limited in what that combination of rock layers causing this character could be.

Class-4 needs addressing further:

● Many observed AVO events are Class-4 (strong trough that dims with offset).

● This could be real when the underlying layer is a higher Poisson’s Ratio than what is above while at the same time the Acoustic Impedance is less. There are very few rock layering configurations that will give you this in practice though.

● This can happen with unconsolidated sands with no shear strength as in over-pressured situations. More likely a coal/lignite, or a clay rich shale.

● Another possibility is a hard shale (marl with high calcite content) above a porous limestone with no dolomitization, as calcite has a high PR.

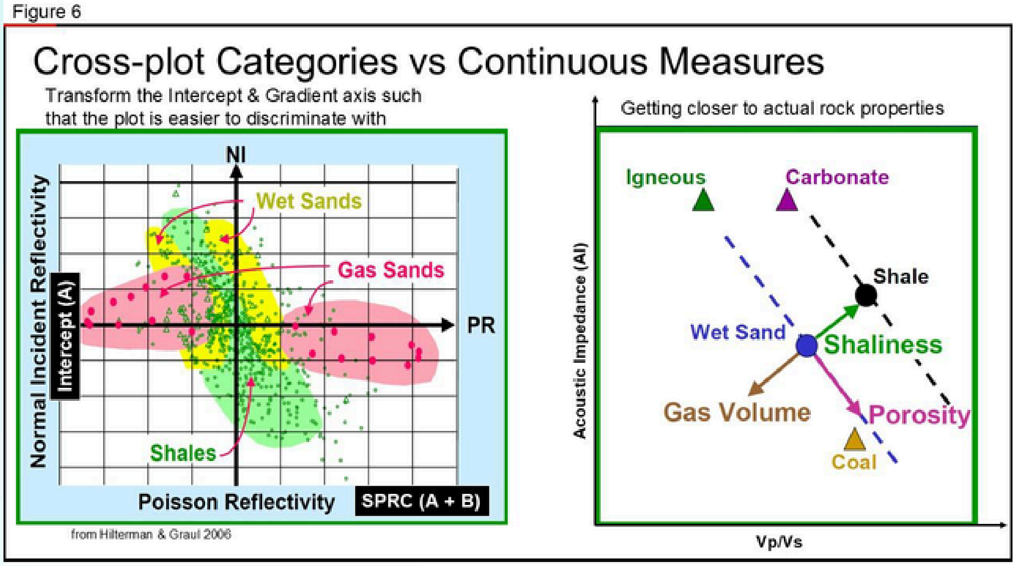
● Or it’s due to insufficient offset scaling on the seismic data.

● Or it could be a thin layer with a tuned Class-3 response. As the ray angles increase the tuning characteristics become more harsh. The top and base reflection deconstructively attenuate, leaving a dimming event that might be observed as a Class-4 event. Which if you had higher frequency data may show it as Class-3.

The exiting event (from the base) is also important, so an extended version of this classification can be useful, as shown on the right hand side for a similar Intercept versus Gradient crossplot, but this time classifying events all the way around the circle. This is sometimes known as the AVO Type, as another way to classify the AVO character for both troughs and peaks. This hasn’t seemed to catch on in the industry and only gets sporadic mention in the literature. By measuring and classifying the Intercept and Gradient of the gathers I’ve generated an attribute of AVO Type shown in the 3rd track of Figure 5. The 3 pay zones in this well-tie on this seismic line shows that the reservoirs are either a Type 1 over Type -4 or a Type 2 over Type -4. While many other pairs of troughs/peaks with a wide variety of AVO Types are seen to exist on this line.

The left hand side of Figure 6 shows a different way to crossplot the AVO reflection attributes. This is PR Reflectivity (Intercept + Gradient) versus Intercept. The gas sands stand

Figure 6



out better here than on the previous Figure 5. But for these reflection attributes it's generally a polygon classification of these crossplot points that is done to show what a particular seismic sample is related to geologically. I'm not a fan of polygon classification as it's easy to miss points that should be in the class as well as getting other points that shouldn't be in the class. While the right hand side is showing AVO inversion attributes of AI and Vp/Vs. Using the inverted layer properties simplifies the plotting of the layer property instead of the top and base reflections of the layer. This puts it into a more continuous prediction grid. Once lithology is predicted then variations from the trend can be implied for fluid type, shaliness and porosity.

In soft rock situations I prefer crossplots of AI v Vp/Vs. While for hard rock the Lame' coefficients may break out rock types better in the crossplot where you show LambdaRho v Lamba/Mhu. This style crossplot is essentially a rotation of the AI v Vp/Vs crossplot and helps optimize the lithology breakout when the rocks are more diagenetically altered.

Figure 7

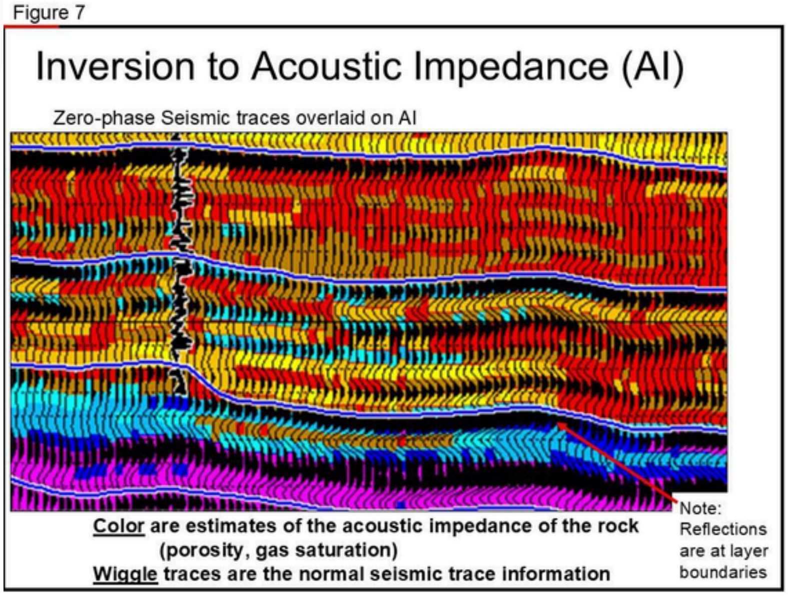
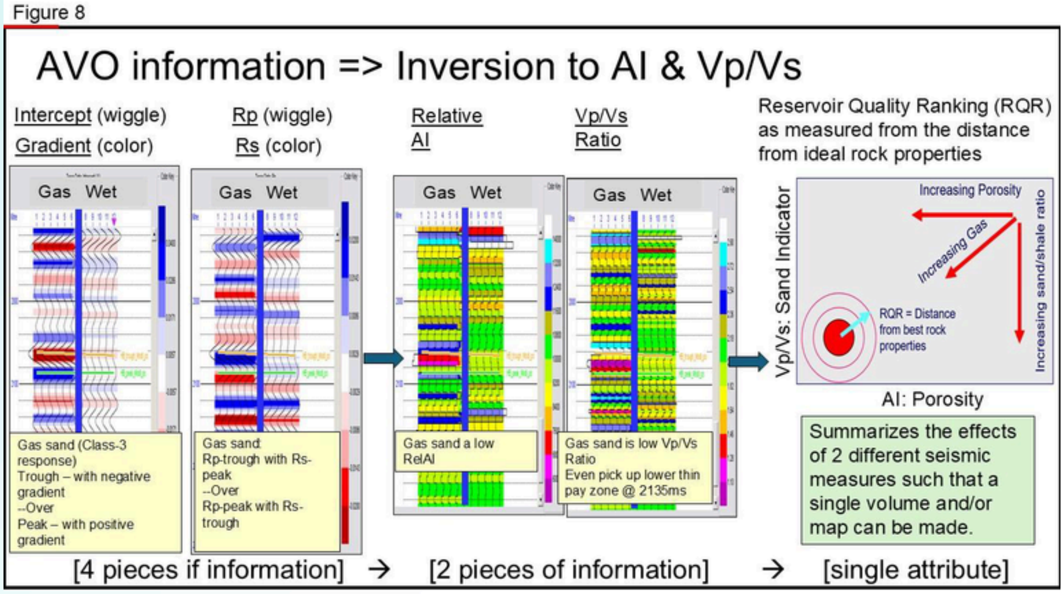


Figure 7 illustrates what seismic inversion does. The wiggle part of the display is the near offset stack section. This is underlain by a seismic inversion of AI shown in color. The amplitude data have been zero-phased (which is a critical part of QI work) and the background impedance model is from interpolated well log data. Since the lowest frequency of the seismic is about 10Hz, the frequencies between about 0 and 10Hz need to be infilled in order to get proper AI output values. You can see the low frequency nature of the output here by the broad layering between horizon surfaces shown by the blue lines.

This background model can be created in many ways and is critical in producing truly quantitative information. In my experience, a not nearly perfect background model is worse than no background model at all. And to get a good background model takes a lot of time and good well log data. It may not sound that difficult as you are only needing information from 0 to 10Hz. The latest Vibroseis data being acquired may record down to 4Hz. But I've never seen good quality information be low about 8Hz. More needs to be done to process the low frequencies properly. You could use the imaging velocities to build a background mode, but that only gets you from about 0-2Hz. Maybe FWI can be used to add information in these low frequencies. It seems there are still limitations in a background model from about 4Hz to 8Hz though. And while that may sound small it has a dramatic effect in the quantitative outputs from inversion.

Seismic inversion can also be extended to handling the AVO information to obtain a more complete rock property prediction. This is a good way of combining data and simplifying the information for analysis. These extra components will require their own background model as well.

Figure 8



Expanding the AVO Attribute list to these inverted quantities:

- Intercept ~ Rp → Acoustic Impedance (AI)
- Scaled Shear Reflectivity (Rs) → Shear Impedance (SI)
- Scaled Density Reflectivity → Density
- Gradient → Gradient Impedance (GI)
- Where (AI / SI) = Vp/Vs and can be transformed into Poisson's Ratio if desired

After making these quantitative rock properties you can then also induce a Rock Physics Template (RPT) onto your inverted output to obtain even more information of the geology, facies and possibly petrography. I contend though that these efforts are not worth the cost in time and known uncertainties in all of the inputs and outputs. Unless of course you have the time and data for this more advanced quantitative result.

I tend to stay with the "Fit For Purpose" mantra. And find that using a constant background model works quite well. When not using a background model the inverted output is usually prefixed by the term "Relative".

Other attributes are better calculated from the original (normal seismic) bed boundary reflections, such as: Coherency, Similarity, Structural dip, etc.

pseudo-Quantitative Interpretation (pQI)

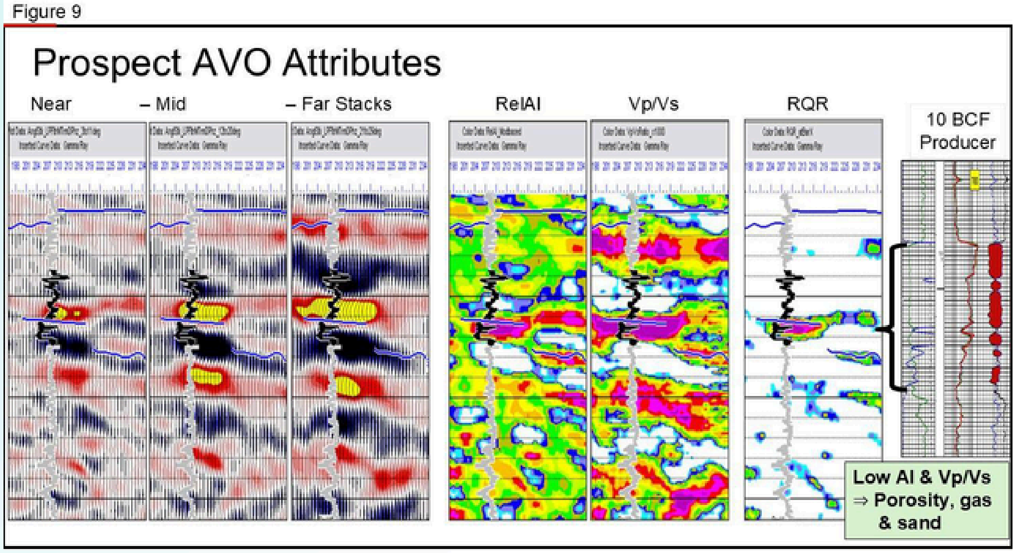
To avoid the extensive effort required for a truly quantitative background model, I prefer a pseudo-Quantitative Interpretation (pQI) methodology:

1. **Relative Impedance Output**: Instead of full quantitative outputs, Relative Impedance outputs are created, scaled using a constant background value from large-scale sedimentary basin values (e.g. a mean AI of 10,000 m/s*gm/cc, from a 4000m/s & 2.5gm/cc average rock).
2. **Trend Reliability**: The methodology focuses on using the trends of seismically derived rock properties, which are considered more meaningful and robust than the actual quantitative values.
3. **Anomaly Ranking**: These trends can then be used to assign a Predictability or Ranking. They can be transformed into a pseudo-Probability for use in uncertainty estimation for prospect evaluation. This approach avoids the limitations of polygon cutoff classifications.
4. **Validation**: By comparing these pQI outcomes to known well analogs becomes a great way to find how robust this prediction is. You can then also scale and use cutoffs if you know the correlations to these analogous outcomes.

Continuing the AVO Modeling Study from above, through an inversion workflow, is shown in Figure 8. Where the left 2 tracks are the AVO reflection attributes of Intercept, Gradient, Rp and Rs for both the gas sand and wet sand case. The middle 2 tracks are then the Relative AI and Vp/Vs of the gas sand and wet sand cases from my pQI methodology. The gas sand is seen to have a very low RelAI and a very low Vp/Vs ratio. While the wet sand is more in the middle value of both RelAI and Vp/Vs ratio. This inversion reduced the amount of information needed to characterize the sands from the reflectivity data from 4 pieces (top and base reflections of intercept and gradient) down to 2 pieces of information (layer properties of AI and Vp/Vs).

A follow-on attribute combines the RelAI and Vp/Vs ratio data into a single predictability measure that I call Reservoir Quality Ranking (RQR). Classically in soft rock situations the crossplot of AI versus Vp/Vs shows the gas sands in the lower left-hand side of low AI and low Vp/Vs. This RQR attribute is then the statistical distance from where on this crossplot a porous gas sand is expected to fall to the associated RelAI and Vp/Vs values from the inverted volumes. The closer those values are to this

Figure 9



expected best value is a distance measured in fractional standard deviations away. This numerical distance (lower is best) is then thought of as the rank order within the 3D seismic cube of predicted anomalies. As an example, an RQR value equal to 0 is finding that best point that you identified on the crossplot and in the 3D volume, while a value of 1 is one standard deviation away from that best point and a 2 is two standard deviations away from that best point. Interesting features for prospecting are typically found within ½ standard deviation away or negative as it may find something better than what you first identified. This continuous valued output measures how close you are to what the expected good outcome is and then could be transformed into a pseudo-probability if you like for predicting a gas sand. It is also easy to volume render using opacity to visualize interesting features in the 3D volume. And could be used to make geobodies that are wrapped by using some low RQR value, leading to cutoffs having a volume greater than some threshold.

Figure 9 shows this same approach on real data for a gas sand discovery. The left-hand side shows a Near / Mid / Far stack of normal seismic data (with PSTM imaging and gather conditioning). You can see the obvious pattern of brightening with offset/angle. Inverting the Rp and Rs AVO attributes from the Fatti algorithm produced the pQI outputs of RelAI and RelSI. Vp/Vs is then the division of (RelAI / RelSI). The AVO anomaly is seen to have a low RelAI and a low Vp/Vs. Summarizing these 2 attributes into the RQR then produces the seismic section on the right-hand side with the very anomalous red feature (very low RQR, near 0) that stands out from the background. This indicates porosity, gas and sand. When drilled this was a 10BCF discovery.

While this "Bright Spot" easily stands out on normal seismic data this pQI workflow creates the attribute throughout and can be used efficiently in a reconnaissance manner. And where the amplitude anomalies are not so strong or simple it also works well in finding the best anomalies within a survey.

Summary and Conclusions

Prospect evaluation along with the associated risk assessment is a complex methodology that requires experience. Historically this has been qualitative using non-standard practices. Given better data and modern software this can be done more quantitatively. A Bayesian approach that I propose can be a method of moving this evaluation process into the 21st century. As a conceptual method I show how to efficiently add information to the system using pseudo-Quantitative Interpretation of seismic data.

While the numerical result from the pQI method appears straightforward, achieving it requires meticulous data processing and attention to detail, and it is typically applied to geologically simple situations. Mother Nature seems to always give you something new to consider after drilling your inventory of prospects. There is always something new to learn. And modifications to the workflows must proceed. Keeping things "Fit For Purpose" is a good way to proceed.

Ways that I've seen this method go wrong include:

● **Low Gas Saturation** (LSG, aka Fizz-Gas, "a little bit of gas goes a long way") can produce strong seismic signatures similar to valid gas prospects.

● **Effect of overpressure** on the shales changing the contrasts between layers which produce the angle dependent reflectivity. Shales usually appear more affected than the sands in this situation.

● **Unconformities** can produce false positives. Since the seismic response is due to contrasts in the impedances across layers, an observed strong gas sand signature could be some other change in AI and SI, along with the Poisson's Ratio. While quartz is the one common mineral that can easily drop the Poisson's Ratio of a rock, there are other ways to do this as well. Or it could be that the bounding layer is an extremely high Poisson's Ratio from a high clay content. In either case the AVO Gradient could appear similar to a gas sand response.

● **Carbonates**, while typically high impedance, good reservoirs can be high porosity, gas filled and of low impedance. Layered below a calcite rich marly shale this contrast can be a strong drop in AI along with maybe no change in Poisson's Ratio such that it has zero gradient, or possibly a Class-4 Gradient that could then be overlooked as an interesting anomaly. If the carbonate is dolomitized then that strongly changes the shear velocity and you could get a Class-3 response from that situation.

● **Poorly processed seismic data** and need for gather conditioning. Post pre-stack migrated data always needs more conditioning steps for the data to be AVO compliant. The data that you are measuring statistically for Intercept and Gradient must be of the same sample support, meaning that the wavelet bandwidth must be the same from near to far. Fitting curves sample-by-sample means that the data must be flat and the usual NMO corrected data is usually not good enough, leading to the need to solve for the RNMO. A phase change Class-2p event is not RNMO and you need to distinguish it from true RNMO events. In high impedance areas the high angle data may be affected by refraction events which will need to be muted out of any AVO analysis, These AVO statistical fits also need to be run on the zero-phased data. Amplitude recovery of seismic data in the time processing domain is also subject to complications. True amplitude recovery methods seem to always fall short. And statistical methods are subject to measuring signal plus noise and not just the signal, which causes limitations in the recovery. And you want to avoid AGC. This leads to an offset scaling problem. I impose a global rock physics average background trend for shale-on-shale events of -2dB as a rule of thumb. Most pre-stack migrated gather data from a contractor do not adjust the data for these effects, unless they add on special services.

The next installment of this series will examine an LSG case study and discuss how to incorporate this issue into the prospect risk assessment of the reservoir, charge, and seal. And more if there is space as I continue this series. Comments welcome.

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