Suggested directions for SEAM Pore Pressure Project
Dan Ebrom
Quantifying seismic velocity derived pore pressure prediction uncertainty

Why?

Pore pressure estimates from seismic velocities are generally delivered with a verbal assessment: “reliable”, “very reliable”, etc.

But how can these verbal assessments be put into a risk matrix?

What is the magnitude of pore pressure uncertainty when derived from seismic velocities?

Additionally, this is a geophysical question that plays well to SEAM’s strengths.

Any reason that additional problems couldn’t also be considered?

No, but

• Need to consider limited budget
• How would multiple research goals get coordinated?
Compaction of smectite by dehydration

Colten-Bradley, AAPG Bulletin, 1987
Figure 3. Porosity loss phases for sands (left) and shales (right). Porosity-velocity data can be used to identify three porosity loss “phases” (Vernik, 1994). Phase I represents sediment-water suspensions. Phase II begins when a sediment achieves a load-bearing structure (its critical porosity), and is dominated by mechanical compaction. Phase III is dominated by cementation and/or pressure solution. Phase II data have the highest sensitivity to pore pressure. Phase II for sands generally extends from porosities of 40% down to porosities of 25–30%. Phase II for shales can begin at porosities greater than 60%, and extend down to porosities of 10% or less. As a result, shales have a much broader range over which pore pressures can be determined from porosity/velocity data. (Figure courtesy of Glenn Bowers.)
Vp compaction trend
Vp/Vs compaction trend: relevant for shallow hazards detection

**Vp/Vs of Mud Rocks**

- Normal
- Synthetic from DT
- Dipole Hi Pressure
- Dipole normal

![Graph showing Vp/Vs of Mud Rocks with depth in feet](chart.png)

- Normal Compaction Vp/Vs
- Offset well Synthetic Vp/Vs
- Overpressure
- Well with dipole
- Offset with dipole

Depth feet:
- 0
- 2000
- 4000
- 6000
- 8000
- 10000
- 12000
- 14000
- 16000
- 18000
- 20000

Vp/Vs values:
- 3.0
- 2.5
- 2.0
- 1.5
- 1.0
• Seismic velocities are not directly sensitive to pore pressure

• Seismic interval velocities respond to the difference between overburden and pore pressure. The difference is called “effective stress”.

• Overburden can also be derived from seismic interval velocities (the “double dip”)

• So

  Pore pressure = Overburden – effective stress

• Overburden is a slowly varying function of interval velocities (because it’s an integral from the seafloor down to the target reflector)

• Effective stress is more rapidly varying, and varies with each interval velocity pick
Usual GOM practice is to assume that compaction is a function of vertical stress only

This works well enough in extensional, undisturbed stress settings, but

fails near salt

fails in toe thrusts

Industry should move forward to modeling (and using) mean stress at a minimum

Shell practice (Hawser, SEG/SPE PP workshop last month) is to use both mean stress and shear stress in thrust tectonic regimes.

Need camclay or MIT-E3 or similar shale compaction model.
\[
\frac{\sigma_{\text{eff},o}}{\sigma_{\text{eff},n}} = \left(\frac{V_p\text{o}}{V_p\text{n}}\right)^3
\]

Eaton’s transform of P-wave velocity to effective stress, where

\( \sigma_{\text{eff},o} \) is the observed or insitu effective stress

\( \sigma_{\text{eff},n} \) is the hydrostatic effective stress

\( V_{\text{p}o} \) is the observed or insitu velocity

\( V_{\text{pn}} \) is the hydrostatic velocity
\[
\frac{\sigma_{\text{eff, o}}}{\sigma_{\text{eff, n}}} = \left(\frac{V_{\text{po}}}{V_{\text{pn}}}\right)^3
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Eaton’s transform of P-wave velocity to effective stress, where

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- \(V_{\text{po}}\) is the observed or insitu velocity
- \(V_{\text{pn}}\) is the hydrostatic velocity

3 for usual disequilibrium compaction, higher for unloading (diagenetic) mechanisms.
So from Eaton’s equation, we can see that small errors in velocity are approximately tripled in terms of effective stress result.

So if an interval velocity had 2% errors on average, then we would expect 6% average errors in output effective stress, even if the transform were perfect.

All this assumes disequilibrium compaction. Higher exponents for unloading larger pore pressure errors for the same velocity input error.

\[ \frac{\sigma_{\text{eff},o}}{\sigma_{\text{eff},n}} = \left( \frac{V_{po}}{V_{pn}} \right)^3 \]

\[(1+\varepsilon)^3 = 1 + 3\varepsilon \quad , \quad \varepsilon \text{ small}\]

Linearization of binomial theorem

Problem solved?
\[
\frac{\sigma_{eff,o}}{\sigma_{eff,n}} = \left(\frac{V_{po}}{V_{pn}}\right)^3
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- So from Eaton’s equation, we can see that small errors in velocity are approximately tripled in terms of effective stress result.
- So if an interval velocity had 2% errors on average, then we would expect 6% average errors in output effective stress, even if the transform were perfect.
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\[(1+\varepsilon)^3 = 1 + 3\varepsilon, \quad \varepsilon \text{ small}\]

Linearization of binomial theorem

But how do we robustly determine the magnitude of interval velocity errors?
Velocity spectra for picking velocities in time domain

From GEOPHYSICS
Taner and Koehler
V. 34, no. 6, Dec. '69, p.867

Time domain
Observe stacking velocity uncertainty increases with two-way time (depth).

**Time domain**

- Velocity spectra for picking stacking velocities in time domain
- From GEOPHYSICS
- Taner and Koehler
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**Fig. 7. Typical velocity spectra display.**

+- 200 ft/s

+- 500 ft/s
- Deeper reflectors have smaller angular input ("aperture")
- Smaller aperture leads to larger uncertainty in velocity
- Rephrased: larger uncertainty means a larger range of velocities that produce the same flattening effect
- Stacking velocity drives interval velocity uncertainty, but the two uncertainties are distinct
- Interval velocity uncertainties are generally higher than stacking velocity uncertainties because interval velocities are a difference of successive stacking velocities, a quasi-derivative
  \[ V_n^2 = \frac{V_{RMS_n}^2 t_{0_n} - V_{RMS_{n-1}}^2 t_{0_{n-1}}}{t_{0_n} - t_{0_{n-1}}} \]
- Derivatives of noisy signals are often even noisier than the input.
- With conversion to interval velocities we finally move into the depth domain.
• In depth migration, two current uncertainty metrics

• **Hit count** – number of rays that interrogate a given cell

• **Aperture** - Range of angles (in vertical plane) that interrogate a given cell

• But might also consider

• **Velocity uncertainty of preceding time-domain stacking velocities** (should be derivable and consistent with aperture metric. Would deviate in presence of uncorrected anisotropy)

• **Azimuthal angular distribution** – advantages of wide azimuth may be due to undershooting laterally heterogeneous features or may be due to multiples suppression – Etgen comment
• In tomography, how much does the final velocity field depend on the starting velocity field?

• How much uplift for final velocity field quality can be achieved through use of basin modeling to produce starting velocity field?
• Salt – a key issue

• Alters stress field, and hence compaction state, and hence alters P-wave and S-wave velocities proximal to salt body

• Impedes seismic illumination of subsalt/nearsalt sediments, and reduces quality of interval velocities obtained from reflection seismic surveys

• Where to get model velocities? – basin modeling for compaction state followed by porosity/siltiness transform to P-wave and S-wave velocities?

• Isotropic velocities acceptable, or should forward model anisotropic velocities?
Salt imaging and stress issues

- Large seismic offsets unavailable due to critical refraction
- Proximal stress perturbations may enhance compaction
- Time/amplitude anomalies below weld
- Salt wing makes imaging difficult
• Seismic geometry for modeling should simulate the best that the industry currently has to offer

• Wide azimuth (even azimuth distribution)

• Long offsets – at least twice the maximum target depth

• Close shot spacing

• Close receiver group spacing
B035 The 2004 BP Velocity Benchmark

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Abstract

In 2004, BP conducted a 2D velocity model estimation benchmark study. The study was open to all interested parties, and was constructed as a blind test of available velocity model estimation/building techniques. The test was based on a 2D synthetic (finite-difference) dataset generated by BP, which was made available to the interested parties. After receiving the data, the participating groups were offered to present their results at the 2004 EAGE workshop and/or provide the results to BP to partake in the overall evaluation.

In this paper, we will present the model used for the benchmark and comment on the results received by BP before the solution was displayed at the 2004 EAGE conference in Paris. The model was designed to cover several issues encountered when estimating migration velocity models in geophysically challenging areas around the world. The model provides velocity estimation problems ranging from a gradient estimation to difficult sub-salt velocity anomaly detection.

Introduction

During the summer of 2003, the EAGE and the SEG co-sponsored a research workshop on velocity model estimation in Trieste (see Jones, 2004). During the workshop it became clear that the current test datasets, such as the Marmousi (IIP), Sigsbee (SMAART JV) and SEG/EAGE 3D models, should be supplemented by a new benchmark/test dataset more suitable for velocity analysis.

During the workshop, several good results were shown from applying a variety of velocity estimation methods to field data, but without knowledge of the true model, it is hard to properly evaluate methods side-by-side. Other results were presented using the classical models mentioned above, but with a known answer, these tests cannot be viewed as unbiased and fully objective. In general it remains hard to fully validate methods without a challenging synthetic dataset where the true solution is known, but kept secret during the testing period. Follow-up discussions confirmed that it was desirable to offer a new dataset that could be used in a blind test to properly validate and test new velocity estimation methods.

The co-organizers of the EAGE 2004 workshop W8 - Estimation of Accurate Velocity Macro Models in Complex Structures - Gilles Lambaré (Ecole des Mines de Paris), Paul Sexton (Total), and Frédéric Billette (BP) kindly offered the workshop as a venue to present the first results of the benchmark. The announcement and invitation to participate in the benchmark was posted on the EAGE web-page in February, and the synthetic dataset was made available for download at the same time. Of the participants, nine groups presented their results publicly during the workshop and twelve sent their derived model to BP by the deadline set on June 6th, 2004.
Figure 1: (top) velocity model and (bottom) density model used to generate the dataset.

Figure 2: velocity model interleaved with the reflectivity. The vertical scale has been exaggerated twice. We can see the complexity of the signal and notice that velocity and reflectivity have similar trends in some areas only.
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There's never been a better time for good ideas