RhoVe Method Empirical Pore Pressure Transform*

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Abstract

The rhob-velocity-effective stress (RhoVe) method represents an interactive approach to pore pressure calibration and analysis utilizing a single transform to convert both compressional sonic and bulk density to common estimates of effective stress and pore pressure where convergence of the two transformed properties offers a robust solution. The RhoVe construct is based on a model-driven, stand-alone set of "virtual" rock property relationships, which at intermediate positions are consistent with Bowers (2001) method default values for the Gulf of Mexico (GoM). Velocity-density conversion functions are mathematically linked to a continuous series of "virtual" velocity-depth normal compaction trend functions. The calculations are limited by bounding end-member curves that provide a basis for intermediate solutions of velocity-vertical effective stress (VES) and density-VES relationships that are applied to a well of interest.

By using the comparative velocity-density function that match an offset well in sonic-density cross-plot space, normal VES for each end-member and intermediate solution can be calculated by integrating the transformed density –"virtual" depth profile (converted from velocity-depth), to produce a set of "virtual" total vertical stress (overburden) estimates that, by the addition of hydrostatic stress (and taking the difference) produces "virtual" normal VES that provides the genetic link between the two rock property relationships (sonic and density). Normal VES is found for any reference velocity-depth or density-depth along the active curve or end members, which is then cross plot as velocity-VES and density-VES. Once calibrated, the construct represents a fully-populated" petrophysical (shale-only) model volume.

The method produces robust solutions, as tested on GoM Shelf and multiple Deepwater wells, and extends the predictability of high-velocity, low-effective stress rock types such as those found in the Deepwater GoM Wilcox-equivalent Paleogene and older section.

Introduction

The rhob-velocity-effective stress (RhoVe) method (Czerniak, 2017) is a two-parameter approach that produces a continuous set of model-driven, stand-alone, "virtual" rock property relationships, which at intermediate positions are consistent with Bowers method default values for the Gulf of Mexico (Bowers, 1995, 2001). Applying the term "virtual" implies clear separation between the stand-alone set of "virtual" rock

property relationships and any actual well data being analyzed. The virtual normal trends are merely tools for constructing the velocity-vertical effective stress (VES), and density-VES family of curves, which are the actual applications applied to a well of interest. At no time is the virtual velocity-depth or density-depth compaction trend series applied in the traditional manner of an Eaton or Equivalent Depth method. The advantage of using a family of curves instead of analytical relations to compute effective stresses, is that the virtual normal trends may be controlled by a single parameter called alpha prime (α', or delimited α), which can be computed interactively. Virtual models provide a systematic approach to account for shale compaction trend changes due to differential mudstone/shale mineralogies and mineral bulk mass fractions.

Virtual velocity and density normal trends are computed from two base curves:

1. Density vs. sonic velocity relation (Figure 1: v-rho)
2. Sonic velocity vs. virtual depth normal trends (Figure 1: v-Z)

Each base or active curve (Figure 1 - dotted lines) is controlled by two parameters: alpha (α) and the a-term that are used to adjust the curve's position between end member curves termed "RhoVE-S" and "RhoVE-Ɛ". Both parameters range between 0.0 (RhoVE-S) and 1.0 (RhoVE-Ɛ). The RhoVE-S end-member represents an empirically derived nominal smectite trend lower bound. Conversely, the RhoVE-Ɛ end-member upper limit should be viewed in the context of an arbitrary mathematical limit for calculation purposes, which can be exceeded under special circumstances.

The sonic normal trend in virtual depth (Figure 1: v-Z) is defined by the parameter alpha (α) while the density-velocity relation (Figure 1: v-rho) is controlled by the a-term parameter. The a-term controls the position of velocity-density relationships between end-members RhoVE-S and RhoVE-Ɛ (Figure 1) and can be input as a mathematical expression to coordinate all intermediate solutions with the a-term input. A catalog of virtual total vertical stress (overburden) curves are found by integration of the virtual density (Figure 1: rho-Z) normal trend (Czerniak, 2017). Hydrostatic pressure is introduced by the addition of a water density profile, or water gradient, which is fixed at 0.465 psi/ft. Taking the difference between the virtual overburden stress curves and the theoretical hydrostatic pressure trend yields virtual normal VES along the active curve and end members. Velocity-VES for a given a-α pair are constructed by combining virtual normal trend velocities and normal VES for a single reference "virtual" depth along the active curve (Figure1, green dot), or the entire active curve and end members. Density-VES relationships for a common virtual reference depth and/or the entire active curve and end members are found in a similar manner. Figure 1 active curve (dotted line) is linked to all other active curves shown for: α =0.37, a =0.6.

In instances where density log data is available for a well of interest, the sonic and density pressure estimates may be calibrated to converge on a robust solution with conformance of the RhoVe sonic-density trend through an active well, high-grade cross plot data cluster. Alternately, the RhoVe velocity-density, and velocity-"virtual" depth compaction trends (controlled by the a-term and α, respectively) may be worked independently in the same manner until convergence of the transformed sonic and density pore pressure estimate is calibrated to drilling history indicators. This "convergent" mode implies that a preferred sonic-density trend is selected by the user for a particular dT-rhob data cluster, and the a-term is chosen independently of α.

Compositional Mode

In what is termed the "compositional" mode, a = γα – αγ and a <= d equations are used to compute the a-term directly from α, which reduces the RhoVe method to a single-parameter model, with a new variable called alpha prime (α', or delimited α). By default, the "compositional" mode reverts to the "convergent mode", with a single, fixed velocity-density relationship for α' values at-or-above what is called the d-term (delimiter).

The "compositional" mode provides a means for making first-pass pore pressure estimates in frontier areas where there is little-to-no offset well control, or in areas where well control is sufficient to calibrate sonic travel time versus rhob density trend series a-term and d-term parameters. It also offers quick approximations of velocity – effective stress relationships that can be used to compute pore pressure for an offset well of interest or an actively drilling well using LWD real-time sonic data with-or-without a corresponding LWD density input. "Compositional" mode implies that all model calculations are performed together, with the results controlled by just the sonic normal trend parameter: α'. Once calibrated, the construct represents a fully-populated" petrophysical (shale-only) model volume.

For the convergent mode, an α' function is substituted to compensate for the position of α relative to a. When linked in the "compositional" mode, intermediate solutions involve: a = γα - αγ (where gamma (γ) is an empirical curve fitting parameter). For the Deepwater GoM study (Czerniak, 2017), γ =2.0 and α'=0.37 (a-term delimiter default = 0.6) is consistent with Bowers (1995) default DWGoM velocity-effective stress relationship and Bowers (2001) GoM velocity-density "slow" trend (otherwise known as Bowers upper bound trend for Δt in shale). These bounds are also consistent with the model proposed by Sargent et al. (2015), who considered Dutta's 2002 telodiagenetic trend as a chemical compaction trend, which applies at greater depths and temperatures – above which, a mudstone may follow different paths while undergoing chemical compaction without unloading, or experience unloading while diagenesis is ongoing.

Conclusions

The rhob-velocity-effective stress (RhoVe) method represents an empirical approach to pore pressure analysis and calibration utilizing a series of model-driven, stand-alone, "virtual" rock property relationships. A two-parameter approach (a and α) is used to construct a velocity-VES and density-VES family of curves that can be applied to a well of interest to calculate pore pressure, where convergence of the two transformed properties offers a robust solution. Cross plots of a versus α data derived from wells in the Deepwater GoM and Offshore Nova Scotia, suggest that both regions track trends that can be fit by equations of the form: a = γα - αγ and a<=d, where delimiter: d is recognized by a plateau in sonic-density cross plot space, and gamma (γ) is an empirical curve fitting parameter. In what is called the "compositional" mode, this set of equations is used to compute "a" directly from α, which reduces the RhoVe method to a single-parameter model (α'). Once calibrated, the construct represents a fully-populated" petrophysical (shale-only) model volume.

This "compositional" mode offers quick approximations of velocity – VES relationships that can be used to compute pore pressure for an offset well of interest or an actively drilling well using LWD real-time sonic data with-or-without a corresponding LWD density input. Advantages of the RhoVe method are that it can be made interactive and fast, relative to other acoustic transform methods. Pore pressure is calculated by directly applying RhoVe-derived velocity-VES and density-VES (no exponents, no compaction coefficients or matrix parameters). The RhoVe

method has conventional and subsalt applications and provides an alternative to the Eaton (1975) method. The RhoVe method represents an empirical approach, and although it incorporates the effects of clay diagenesis and unloading, does not depend on a thermal model or the mechanics of unloading for pore pressure analysis.

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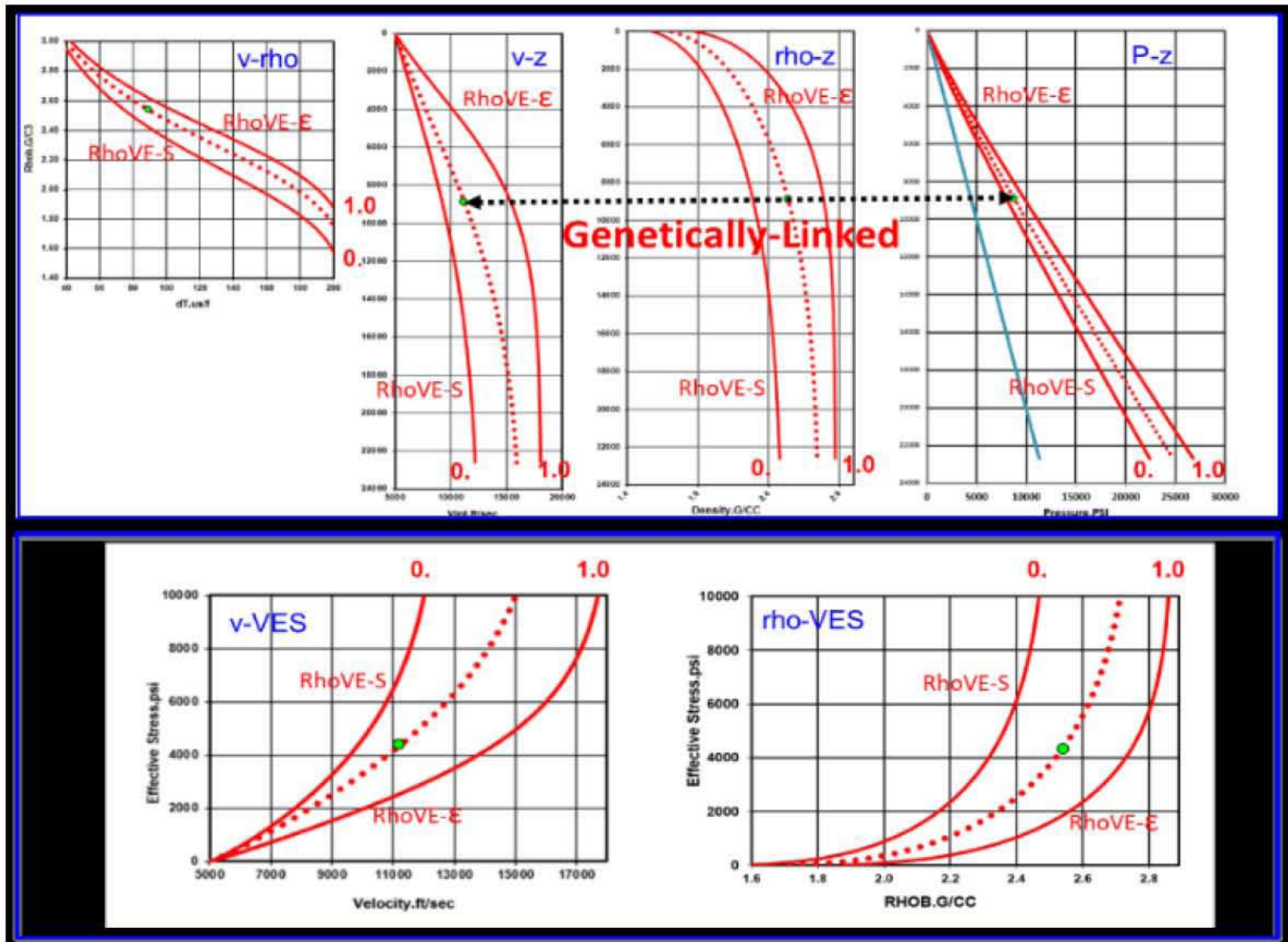
Figure 1. Summary presentation of RhoVe concept "virtual" model. Nominal RhoVE-S and RhoVE-Ɛ end-member bounding curves (bold red curves on all plots) are tethered together for the one-parameter model and correspond to α' inputs of 0 – 1.0, respectively. The solutions generated in the RhoVe method "virtual" model (top half) are used solely for the purposes of constructing the series of velocity-VES and density-VES solutions (bottom half) that are applied to a well of interest. Dotted pattern represents the active curve that is linked to all other active curves (see text for discussion).