RhoVe Method II: Empirical Density-Temperature-Effective Stress Transform*

Matt Czerniak[1]

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[1]GCS Solutions, Inc., The Woodlands, TX, United States (matt@geopressuresolutions.com)

Abstract

The rhob-velocity-effective stress (RhoVe) method represents an empirical approach to pore pressure analysis and calibration that utilizes a series of model-driven, genetically linked “virtual” rock property relationships. The method is fundamentally a two-parameter approach (a-term and alpha) that are used to construct a velocity-vertical effective stress (VES) and a density-VES family of curves that can be applied to a well of interest where convergence of the two transformed properties offers a robust solution. When the a-term is set as a function of alpha, RhoVe method is reduced to a single parameter (alpha’) that includes the effects of compositional changes related to clay diagenesis. A sub-regional study of subsalt wells located in the south-central Deepwater Gulf of Mexico (DW GoM) confirmed the presence of a plateau, or upper limit in a-term relationships (sonic versus density cross plot space), in a narrow band that approximately coincides with Bowers published Gulf of Mexico “slow” trend for shales and is consistent with the effects of ongoing chemical compaction. Once calibrated, the construct represents a fully-populated” petrophysical (shale-only) model volume that can be queried and interrogated to perform advanced calculations.

A new method of calculating pore pressure from temperature is presented that both frames the structural-stratigraphic history of fine-grained clastics in a sub-regional setting and allows for an interpretation of local diagenetic effects. Post-drill pore pressure analysis results for the initial subsalt study area were expanded to include other (non-subsalt) areas of DW GoM and Shelf regions, and the RhoVe method was extended to produce a family of density-VES relationships applied as a function of temperature (RhoVe-T), that can account for the effects of bound water expulsion and other diagenetic factors related to load transfer and ongoing chemical compaction. The method utilizes a single master power law reference relationship between temperature (in degrees Fahrenheit) and alpha’ that is applied as an instantaneous series to wells that span the Gulf of Mexico Shelf and Deepwater regions. The study documents the effects of apparent load transfer due to late-stage S/I clay layer reorganization that is initiated at mudstone densities on the order of 2.4 gm/cc (+/-0.05gm/cc) and ~200° F (95° C). Apparent load transfer continues beyond the threshold temperature until an equilibrium state is achieved within the mudstone fabric that allows clay densities to once again increase, marked by a concomitant increase in effective stress.

Recognizing the delay in the temperature window beyond the initial threshold temperature (between 200-250° Fahrenheit) allows for a model-driven, deterministic prediction of increasing compaction trend relationships for the deeper section. Density-derived alpha’-temperature power

law solutions are directly extended to include sonic velocity and acoustic impedance relationships tied to VES. The temperature-alpha' power law function transforms both sonic and density data for the entire stratigraphic section, including Plio-Pleistocene/Miocene/Oligocene and older Wilcox-equivalent Paleogene shales and mudstones.

Accounting for the effects of ongoing chemical compaction and diagenesis using alternate associations extends the predictability of high-velocity, high-density, low-effective stress rock types such as those found in the DW Gulf of Mexico lower Miocene and Wilcox-equivalent Paleogene mudstones and older onshore unconventional shale-play reservoir sections.

Introduction

Over the past several years, progress has been made by many industry practitioners toward developing and refining new pore pressure analysis and prediction methods that relate changes in effective stress to variations in temperature and diagenesis, namely smectite-illite transformation (e.g., Alberty and McLean, 2003), or to processes related to sediment unloading (Bowers, 1995). More recently, Sargent et al. (2015) considered Dutta's 2002 lower eodiagenetic (smectite) trend in sonic-density cross plot space as a mechanical compaction limit and Dutta's telodiagenetic (illite) trend as reflecting the effects of ongoing chemical compaction. Their ongoing chemical compaction trend is comparable to Bowers (2001) published upper bound trend for Δt in shale (a.k.a. Bowers GoM "slow" 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.

A sub-regional study of wells located in the south-central Deepwater Gulf of Mexico (DW GoM) (Czerniak, 2017) confirmed the presence of a plateau, or upper limit in a-term relationships (sonic versus density cross plot space), in a narrow band that approximately coincides with Bowers published Gulf of Mexico "slow" trend for shales and is consistent with the effects of ongoing chemical compaction. The transition from mechanical to chemical compaction follows closely with the onset of the smectite to illite reaction in mudstones, which commences at between 60-70° C (140-158° F) and ends (for the most part with the ~80% stable form I/S) by about 120° C (248° F; Lahann, 2017). In some cases, stiffening of the mudstone-shale matrix may be observed, where there is an overlap between the illitization process and the dissolution and reprecipitation of microcrystalline quartz (a byproduct of illitization). These observations are supported by recent advances in EMI (electron microbeam instrumentation) and sample preparation procedures, which suggest that the principal diagenetic processes that affecting sandstone and limestone compaction and cementation, also operate in mudrocks (Milliken, K., 2017). Discoveries of fine-grained micropore filling quartz cement found in Upper Cretaceous mudstones offshore Norway reveal the importance of micro-quartz cementation and its impact on mudstone and shale properties (Jahren et al., 2009).

Lahann and Swarbrick (2011) proposed that the process of fluid pressure increase owing to illitization is best viewed as the result of load transfer facilitated by framework weakening. The diagenetic processes active in the shales change the mineralogy, volume and the (preferred) orientation of the load-bearing grains. When these changes are not accompanied by fluid export, some of the load is transferred to the fluid phase (inelastic unloading). This mechanism differs from a reliance solely on fluid expansion and elastic unloading (Bowers, 1995, 2001), and results in an increase in preferred orientation of clay particles during conversion of smectite to illite. Lahann and Swarbrick (2011) interpret preferred orientation in shales to result from two processes: first, dissolution of detrital grains followed by pore collapse; and secondly, neoformation of preferentially aligned minerals.

Ongoing chemical compaction, or the progressive evolution from a mudrock to a truly lithified shale (applicable to unconventional applications), is driven principally by shale diagenesis through thermodynamics, kinetics and temperature. Thermodynamic approaches utilize RhoVe-T (executable) using density, sonic and their product - acoustic impedance as input versus temperature that may be directly applicable to geologically mature shale play reservoir sections and unconventional plays.

RhoVe Model Construct

An immediate advancement of the RhoVe method (Czerniak, 2017) is the addition of the density log, which is now in play as a pore pressure indicator. 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 (GOM; 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 RhoVe method also handles unloading effects without the express need to reconstruct Vmax (using Bowers traditional method). In instances where density log data are 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.

Compositional Mode

The “compositional” mode implies that a preferred sonic-density trend is automatically selected for a particular dT-rho cross plot data cluster, and the a-term is dependent on alpha (α) (i.e., $a = f(\alpha)$) (Figure 1). In what is termed the “compositional” mode: $a = \gamma\alpha - \alpha\gamma$, where $a <= d$. Both 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’; otherwise termed 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 the d-term mathematical delimiter, which simulates the plateau recognized in sonic-density cross plot space. For the DW GoM study (Czerniak, 2017), γ =2.0 and α’=0.37 is consistent with Bowers (1995) default DW GoM velocity-effective stress relationship and Bowers (2001) GoM velocity-density “slow” trend (otherwise known as Bowers upper bound trend for Δt in shale).

The results from multiple well datasets in the Gulf of Mexico suggest that calculations involving the RhoVe method “compositional” mode are appropriate for temperatures less than about 100-120° C and are more applicable to younger offshore sediments. At greater depths, mudstone to shale transformation continues, and is identified by changes in physical rock property relationships where ongoing chemical compaction and shale diagenesis are controlled principally by temperature.

RhoVe T Method

A new empirical, thermal-based approach is presented that provides pore pressure solutions using a reference relationship between temperature and α' (RhoVe T) that helps to frame the structural-stratigraphic history of fine-grained clastics in a sub-regional setting and allows for the interpretation of local diagenetic effects. Utilizing temperature also allows for an assessment of chemical compaction effects (Sargent et al., 2015), which have been largely under-explored by most PPFG practitioners.

A Power Law trend (see Figure 2; equation 1) acts as a guide function for assigning α' from a corrected temperature/depth profile for a well of interest. An infinite number of compaction trends are available (between 0 and 1.0) and each shale discriminated data point has its own unique compaction trend assigned to it via the Power Law guide function:

$$\alpha' = k\,(T^\circ F - \Delta T)^b \qquad [1]$$

Where:

k: 6.10E-08
b: 2.968
ΔT: scaling parameter (+/-) in ° Fahrenheit

Each (GR) shale discriminated (sonic, or density) data point in temperature/depth is run through the RhoVe "virtual" model via an instantaneous series of α' compaction trends using an executable script. All variants away from the master power law trend (including a GOM Shelf and Onshore trend) involve bulk shifts of the main power law function by a single variable input parameter: ((+/-) ΔT) making the RhoVe T method a single parameter approach. The same temperature- α' power law function profile can be applied in real time, post drill analysis and predrill for an undrilled location using a seismic stacking/migration interval velocity model.

Based on the results of a 20-well GOM-wide study, the RhoVe T temperature-based method produced a margin of error in accuracy of <7% (as measured in temperature); which translates to +/-0.5 PPG Equivalent Mud Weight (EMW) for 16 out of 18 DW GoM wells that align at-or-near the master power law guide function (as tested on both (12) subsalt and (6) non-subsalt wells located in the DWGoM) - "out-of-the-box" without the need to calibrate against local mud weight histories (in the traditional sense).

The master power law function (with ΔT = 0) includes six subsalt wells and all six of the DW non-subsalt wells – (12 in total) fall directly on the main trend (Figure 3). The remaining four subsalt wells are part of the 16 wells that are within +/-7% of the main power law trend as measured in temperature (which translates to about +/-0.5 PPG.EMW). The remaining two wells (Kaskida and Shenandoah with ΔT = -55o F) show what is termed a "subsalt effect" (or are diagenetically restricted) – likely due, in part to suppressed thermal histories.

Two GoM Shelf wells define the GoM Shelf & Onshore trend (ΔT = +75° F). The SMI23-5 well bottom hole section experienced unloading in a highly overpressured shale, beginning at ~200° F (95° C). The one remaining GOM Shelf well (described by Rask (1997) and reviewed again by Lahann (2017)), is believed to reflect its sedimentary provenance (a Pliocene depo-center) and is found to be oversaturated with respect to potassium relative to other wells at similar compositions and temperatures, suggesting that the illitization process was somehow inhibited, possibly due to the presence of high levels of Na+, Ca2+ and Mg2+ in the pore fluids themselves, even if potassium was available for the transfer (Roberson and Lahann, 1981, Roaldset et al., 1998). The GoM Shelf and Onshore trend converges with DW GoM PI526 and MC204 well bottom-hole sections.

Breakover Effect

The "breakover effect" describes the observation that pore pressure interpretations for (hotter) wells exit the main power law trend likely driven in response to rising temperatures because of higher geothermal gradients. The point where they break over coincides with where the wells egress the load transfer phase of illitization (I/S). Framework weakening, pore collapse and clay mineral realignment (Lahann and Swarbrick, 2011), modify the fine-grained sediments that follow, reflecting the newly formed, more ordered illite clay particle fabric in a preferred layer orientation (R=1; Polastro, 1993).

The linear breakover compaction trends are conceptually aligned with what can be thought of as the more traditional normal trend associations, like Eaton and Bowers. For example, Bowers default DW GoM patented velocity-effective stress relationship (shown slightly inclined in Figure 4) corresponds to an α' value of approximately 0.4, which is close to the onset of the load transfer effect at ~200° F (95° C).

The collective observation of hotter DW (non-subsalt) wells experiencing breakover effect and subsalt wells that are largely unaffected suggest that the Power Law trend may represent a critical threshold in thermally driven effective stress behavior related to illitization. DW GoM sediments close to their maximum temperature and burial depth may reach a nexus point once their temperature-depth profiles reach the power law trend. The effect of temperature along with the presence of K+ are known to be primary drivers for illitization to proceed (Freed and Peacor, 1989; Roaldset, et al., 1998), however time is also a critical factor. The ubiquity and prevalence of the power law trend associations under varying temperature histories suggests that in the presence of sufficient K+, illitization may proceed even at reduced temperatures (Figure 5).

Conclusions

By performing (sonic) velocity-VES or density-VES analysis as an (executable) instantaneous series in temperature, versus the traditional method of modeled departure from a low-frequency velocity-depth normal compaction trend (like Eaton), there is a degree of freedom in the direction of increasing (or decreasing) velocity and density (in a direction parallel to the compaction trend), that compensates for variations in clay content, volume, etc., which are reflected in the sonic or density rock property measurement. The instantaneous series application allows for departure to higher density/faster velocity sediments like the mudstones/shales in the age-equivalent Wilcox. Accounting for the effects of ongoing chemical compaction and diagenesis using alternate associations extends the predictability of high-velocity, high-density, low-effective stress rock types such as those found in the DW GoM lower Miocene and Wilcox-equivalent Paleogene mudstones and older onshore unconventional shale-play reservoir sections.

The results of this study suggest that all fine-grained clastic sediments in the Gulf of Mexico follow similar thermally induced-effective stress behavior, and that pore pressure may be calculated for any well in the GoM by changing one single input parameter: (+/-) ΔT. In other words, the results of this study suggest that all wells in the GOM Shelf or DW (subsalt or non-subsalt) follow the same power law temperature- α' guide function and can be modeled and computed using only a simple shift in ΔT. The method has been tested under various application scenarios and has proven to work for predrill, real-time and post-drill analysis using sonic and/or density (do not need both, but best if both are available).

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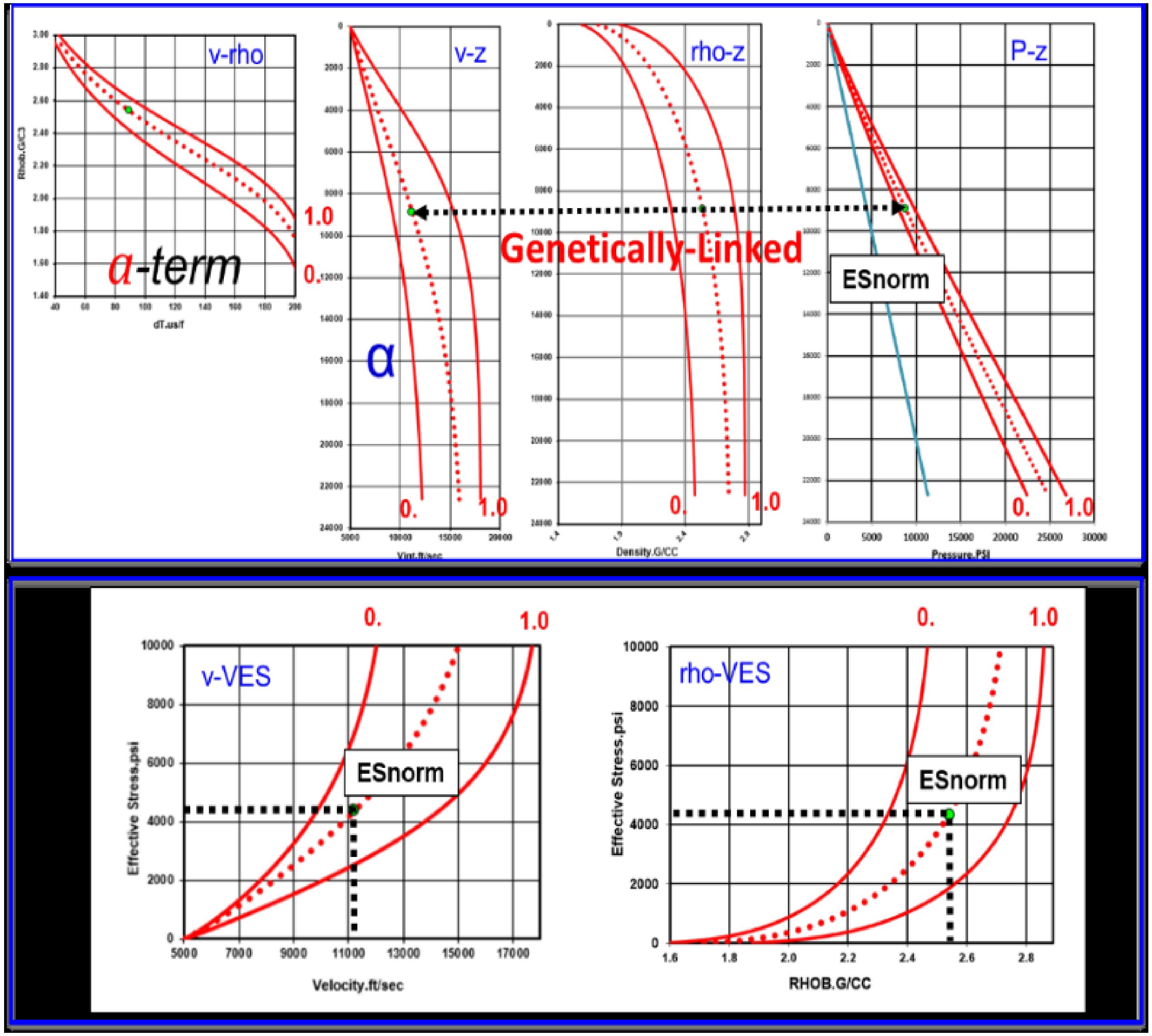


Figure 1. Summary presentation of RhoVe concept "virtual" model. Nominal RhoVE-S and RhoVE-Ɛ end member bounding curves (bold red curves on all plots) correspond to values of 0-1.0, respectively. The active curves (red dotted pattern) are tethered together ("compositional" mode) for the one-parameter model and are linked to all other active curves in each of the rock property relationships. The solutions generated in the "virtual" models (top half) are used solely for the purposes of constructing the series of velocity-VES and density-VES solutions (bottom half) that are the actual applications applied to a well of interest. The active curves are shown for α =0.37, a =0.6; which coincides with both Bowers default DW GoM v-VES and upper bound Δt in shales. (See text for discussion).

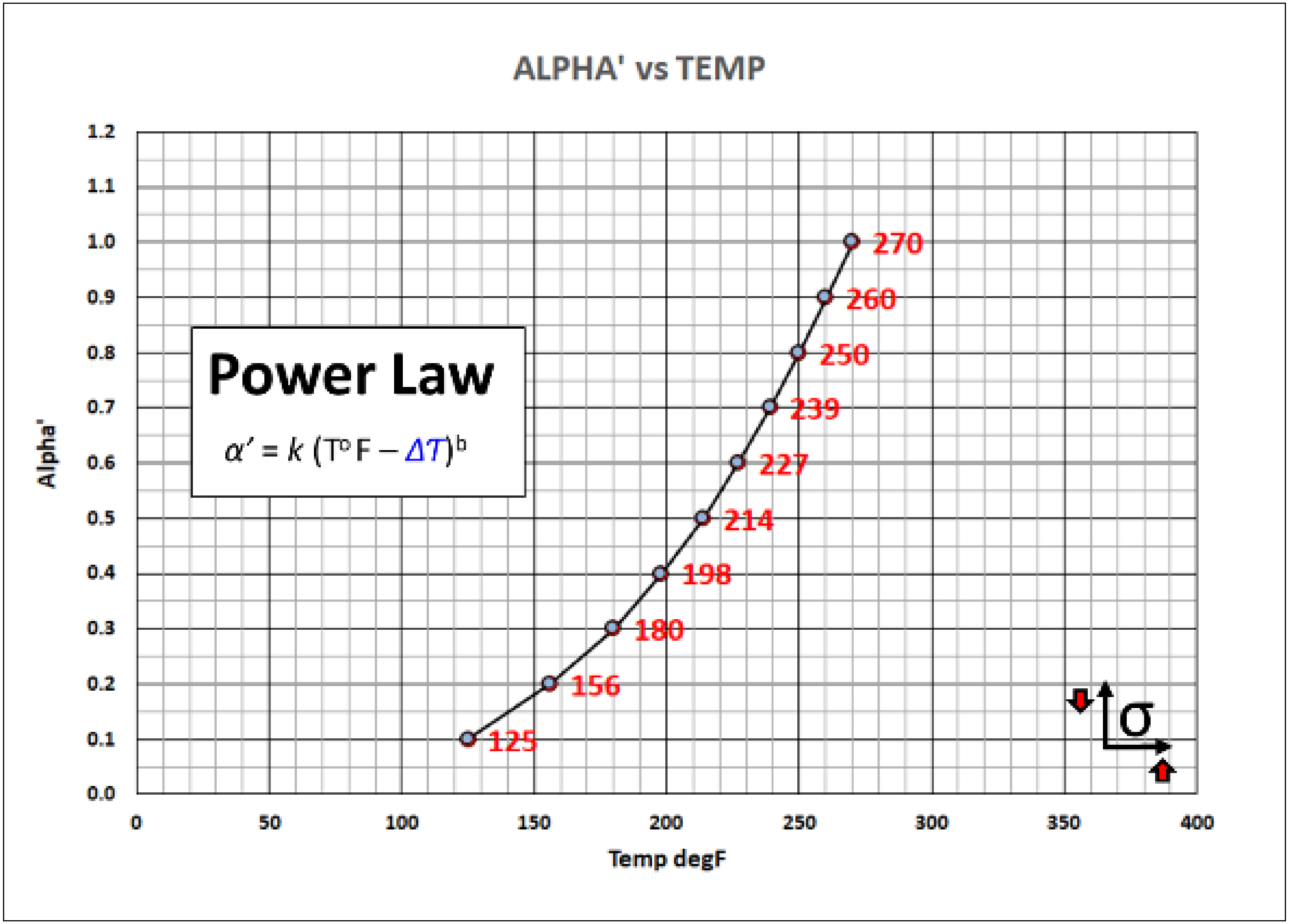
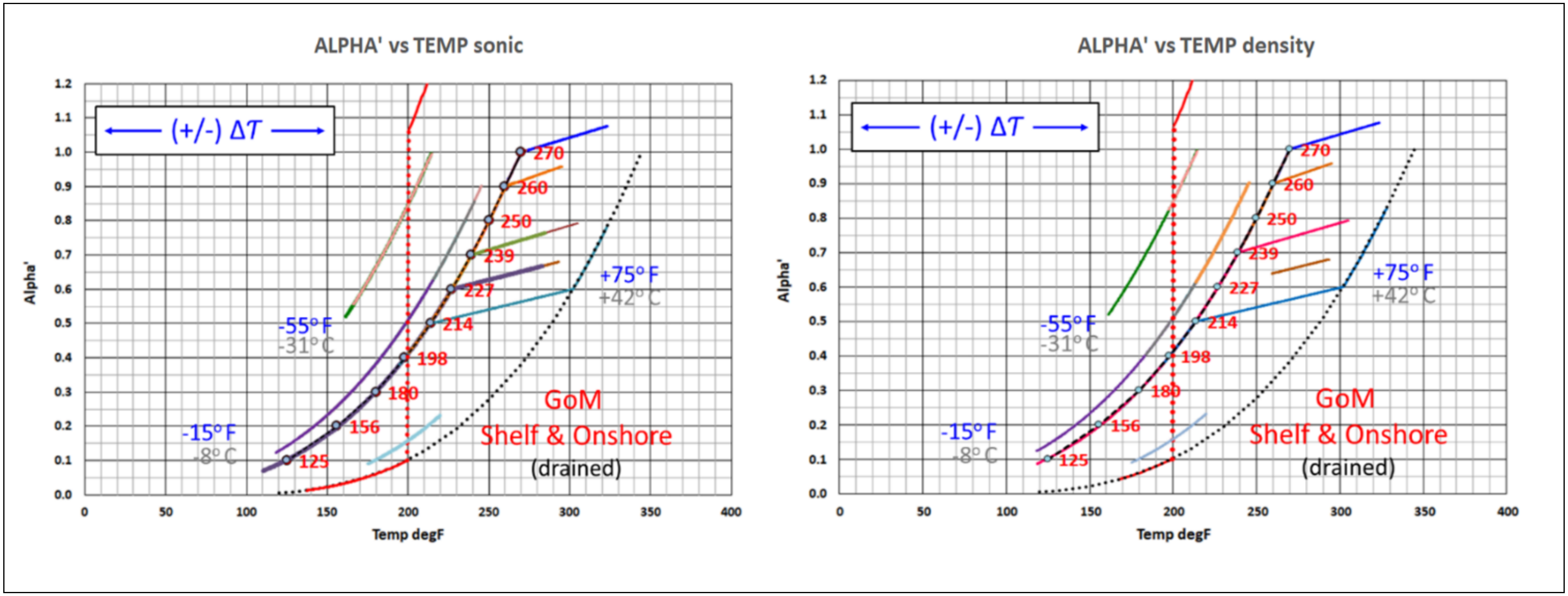


Figure 2. A master Power Law relationship between temperature and α' guides the RhoVe T model for the calculation of pore pressure for wells spanning the entire Gulf of Mexico. A single transform converts dtco (sonic) and rhob (density) for Plio-Pleistocene, Miocene, Oligocene and Paleogene (Wilcox-equivalent) in one, single transform. It applies to both sonic and density data, for predrill, real-time and post-drill analysis. Inset (lower right) is orientation of relative effective stress increase or decrease indicated by red arrow.



Figures 3a and 3b. Temperature - α' power law guide function (light blue dots: 0.1 increments of α' with temperature annotation (To F) in red) and calibrations for both sonic (5a) and density (5b) (identical), with 20 well calibrations directly visible on the plots. Blue annotations are (+/-) ΔT ° F (gray ΔT ° C). Colored lines represent actual well transforms (e.g., blue curve visible at the top of the main power law trend represents calibration for BP KC102 Tiber-1). Red dotted pattern connects SMI23-5 overlying silty/sandy (drained) shales in GoM Shelf and & Onshore section with unloaded shale beginning at 200° F.

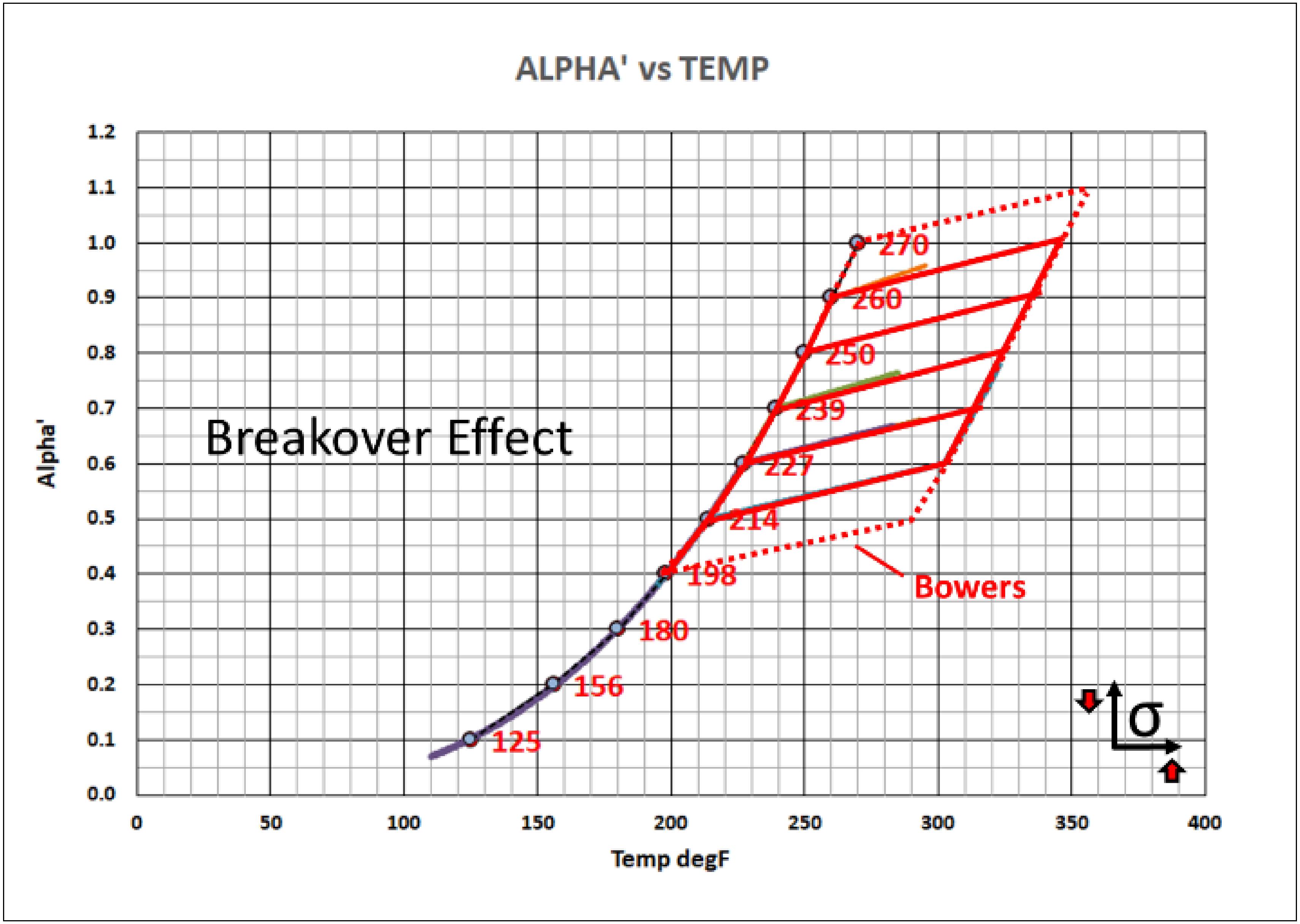


Figure 4. “Breakover effect” and model template (see text for discussion).

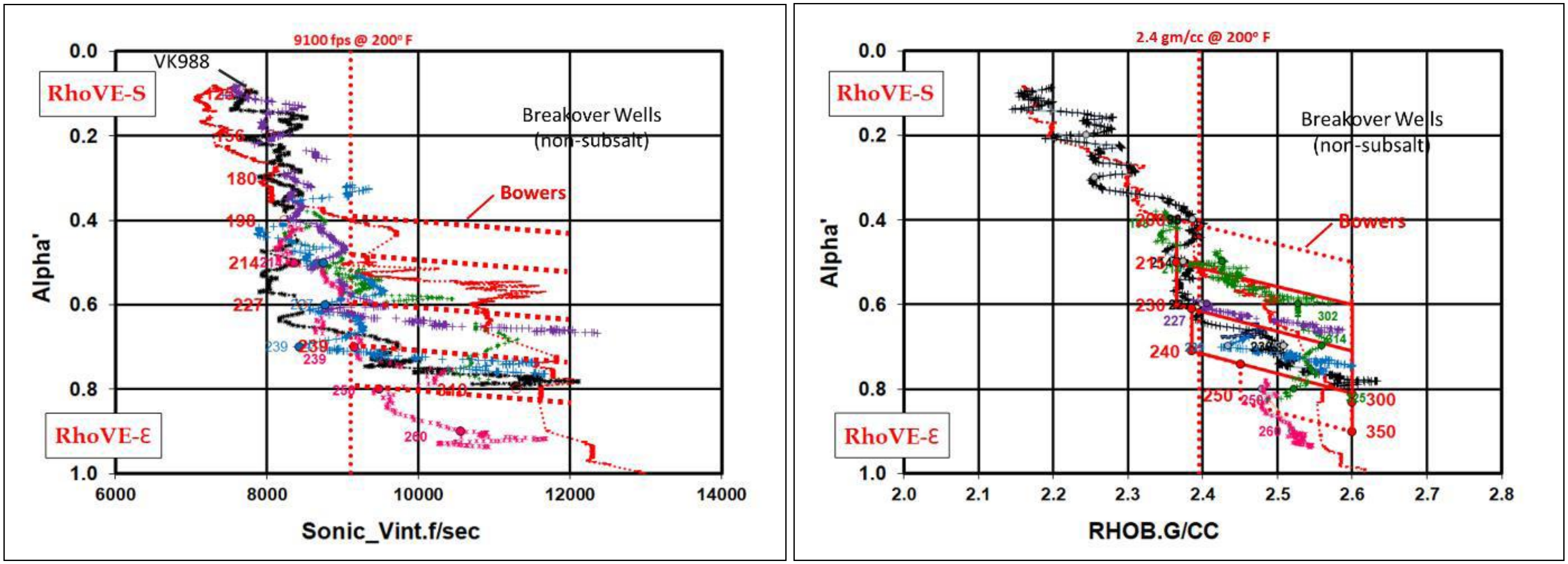


Figure 5a and 5b. Composite DW GoM (non-subsalt) well data cross-plot profiles for sonic (vint; 5a) and density (rhob; 5b) represent y-axis data flattening on α' (0-1.0) from v-VES and rho-VES calculations (see Figure 1). "Breakover effect" and critical threshold values (9100 fps and 2.4 gm /cc at 200° F, respectively) with annotations in red that represent delayed exit temperature (T ° F; see text for discussion). Model templates are shown for sonic (vint) and rhob (density) (solid and dashed red lines) with an approximation of Bowers default trend values as calibrated from the initial α' "compositional" mode RhoVe method "virtual" model (shown slightly inclined), which is consistent with an α' value of ~0.4 (0.37; Czerniak, 2017).