Influence of horizontal and vertical stresses on Vp-Vs trends

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Summary

Some rock properties show surprisingly stable relationships, to the extent that any deviation therefrom should be regarded as a signal of anomalous behavior. One of these stable relationships is the linear trend between compressional (Vp) and shear velocities (Vs), which is observed for both sandstones and mudstones. We infer that anomalous stresses, notably deviations from the basin-wide relationship between horizontal and vertical effective stresses, may cause deviations from the basin-wide Vp-Vs trends. An anomalously high or low shear velocity can therefore be indicative for an anomalous stress regime.

Introduction

Industry and Shell exploration success in the past decades was largely based on understanding properties of sands and bounding mudrocks in extensional settings. As one particular example, a very stable linear relationship has been observed between longitudinal and shear velocities. Such a relationship for mudrocks (Castagna et al., 1985) is often referred to as the "mudrock line". While the exact reasons for the stability of these relationships within a basin are not well understood, they have been extensively relied upon in petrophysical and geophysical practice. If Vp-Vs measurements deviate from this line, one must argue there should be a clear cause.

A robust Vp-Vs-trend derives from a stable relationship between horizontal and vertical effective stresses

Empirical linear relationships between P- and S-wave velocity in mudrocks have been widely known for a long time. For Gulf Coast mudrocks, (Castagna et al (1985) and references therein) for example presented a version of such relationship called the "mudrock line"

$$V_s = aV_p - b \quad , \quad (1)$$

where $a = 0.8621$ (dimensionless) and $b = 3846$; b and velocities given in ft/s. A remarkable feature of such V_p-V_s empirical relationships compared to other petrophysical correlations is the low standard deviation of the data points from the trend estimated to be only around ~ 200 ft/s.

Similar robust linear trends have been established for other basins. The parameters for these trends differ slightly from these above possibly due to variations in mineralogy, salinity and local stress conditions. Vp-Vs trends for wet sands are equally stable after correction for pore fluid differences.

Effect of horizontal and vertical effective stresses on velocities over a short time period

Rock physics measurements in the lab on hard rock and highly lithified samples indicate that the P-wave velocity is predominantly controlled by the effective stress acting in the direction of wave propagation [see e.g. Nur, Simmons (1969), and the observations by Prioul and Lebrat (2004) in the analysis of a number of experiments]. While the effective stress perpendicular to the direction of propagation does affect the P-wave velocity, its influence is relatively minor in comparison.

The situation is drastically different for S-waves, which is almost equally sensitive to stresses in the direction of propagation and to stresses perpendicular to this direction in the polarization plane. Such behavior was predicted by non-linear elasticity (Hughes and Kelly, 1953). The dependence of shear-wave velocity on both axial and radial stresses has been observed on core samples of various rock types (Nur and Simmons, 1969; Bakulin, 1975). Such dependence was successfully exploited in various seismic and acoustic techniques aimed at estimating current-day horizontal stresses or their temporal variations (Bakulin, 1975; Bakulin and Bakulin, 1991; Bakulin et al. 2000; Sinha et al, 2002; Herwanger and Horne, 2005).

The relationship between the 3D stress fields and anisotropic P- and S-velocities in sedimentary rocks has been studied in detail by Prioul et al. (2004), Sarkar et al. (2003) and Bakulin et al. (2004). They confirmed that shear-wave velocity is controlled by both stress in the direction of propagation and one of the stresses perpendicular to this direction. The velocity of a vertically propagating shear velocity is mainly controlled by horizontal stress acting along the polarization direction while the orthogonal horizontal stress has a minor influence (Bakulin et al., 2000; Sarkar et al, 2003; Prioul et al., 2004).

There is therefore an important difference between the sensitivity of compressional and shear velocity of a rock to stress. The change in compressional velocity depends mainly on a single stress component; the change in shear velocity depends on two stress components that are almost equally important.

These observations relate all to measurements in which non-elastic effects are not incorporated. Non-elastic effects and the relaxation of stress will however be important in the evolution of rock velocities over geological time.

VES-HES path and its effect on velocities over geological time

In an extensional basin, a rock will be subject to a vertical effective stress (VES), larger than the horizontal effective stress (HES). The existence of stress anisotropy, the dependence of velocities on 3D stresses and the existence of stable Vp-Vs trends are all well recognized, but were often viewed in isolation. In order to reconcile the stability of the Vp/Vs trends with the outlined dependence of P- and S-wave velocities on 3D stresses, one needs to assume that in many basins there is a well-behaved relationship between horizontal and vertical (effective) stresses similar to the Vp-Vs trend itself. We suggest that such the relationship between VES and HES is comparatively stable in many extensional settings, for which the majority of the in-situ Vp-Vs regressions were derived. Let us outline some heuristic arguments supporting this conclusion.

In practice, velocity-based pore pressure prediction is based on the relation between compressional velocity and vertical effective stress. These dependencies are defined with "normal compaction trends" (Hottmann and Johnson, 1965). The practice of describing compaction and all related quantities as a function of a single parameter - typically taking vertical effective stress as a proxy - is well established in extensional basins. In essence, and in due disregard of more complex situations where e.g. unloading may play a role, pore pressure prediction rides on a unique and exclusive relationship between Vp and effective stress. Departure of velocity from the normal trend is interpreted as a deviation from the VES trend and hence as an indicator of overpressure.

Such a simple scheme does not apply to shear velocity because it is controlled both by VES and HES. Vertical total stress is largely determined by the weight of the overlying rocks and fluids and has to be continuous at horizontal interfaces. In contrast, the behavior of horizontal stress is apparently much less controlled. Total horizontal stress does not need to be continuous at an interface even though vertical stress is continuous since this is not required by boundary conditions of full bonding. Thus, at first, one may expect little consistency in the variation of total horizontal stress as well as HES with depth. However the stable Vp-Vs relationship defies this expectation. Imagine that the VES-HES relationship would be unpredictable and behave irregularly from location to location in an open basin. Then more than likely we would find an immediate imprint of such behavior on shear-wave velocity manifesting itself as a departure from established Vp-Vs trend. It would also impact other rock properties like porosity, density and resistivity due to the modified compaction under different 3D stress conditions with varying mean effective stress and deviatoric stress (Goulty, 2004). None of these effects is typically observed in an extensional setting and Vp-Vs falls onto existing trends with an amazing consistency (Castagna et al., 1985).

Therefore we suggest that extensional settings are characterized by a comparatively stable relationship between VES and HES.

As current day P- or S-velocity is the result of progressive compaction, with both elastic and inelastic/irreversible processes contributing to the evolution of the rock, we should expect deviations from established Vp-Vs trends if the stress state has deviated substantially from the normal (extensional regime) VES-HES trends.

Rock physics transform between Vp-Vs and VES-HES

We conclude: *a linear trend in Vp-Vs derives from the existence of a similarly well-defined stress trend in VES-HES space defining the regional "normal extensional compaction curve". If subsurface stresses are consistent with this VES-HES trend, then Vp-Vs also remains on its trend. If the stresses deviate from the normal stress path during any part of geologic history, Vp-Vs can be expected to experience some deviation from its linear trend*.

To make this more visual, it is instructive to plot corresponding trends in Vp-Vs and VES-HES coordinates respectively (Figure 1). If stresses obey the normal relationship (pink line on Figure 2a), then Vp-Vs remains on the linear trend shown as pink line on Figure 2b. If the stresses reduce through e.g. an unloading process, and horizontal stress experiences a smaller decline than expected for a given amount of decrease in vertical effective stress (Figure 1a), then the P-wave velocity decreases by the amount corresponding with the decrease of vertical stress, whereas the shear velocity experiences a partial decline and the resulting point in Vp-Vs space falls above the trend line (Figure 1b).

Likewise, Figure 2a,b covers the alternative unloading scenario when horizontal stress experiences a larger decline than expected for a given decrease in vertical effective stress. In this case Vp reduces according to VES, but Vs decreases more and the resulting point in Vp-Vs space falls below the trend line (Figure 2b). Therefore, we establish a visual correspondence between stress and velocity domains when being "above" or "below" the stress trend line implies being "above" or "below" the velocity line, while staying on the trend in the stress space implies remaining on the trend in velocity space.

In this study, we are concerned with the qualitative expression of the effect. We examine "anomalous cases" where stresses are believed to deviate from established

VES-HES and attempt to verify: 1) whether a Vp-Vs deviation is observed as predicted; 2) whether the sign of this deviation is consistent with the predictions.

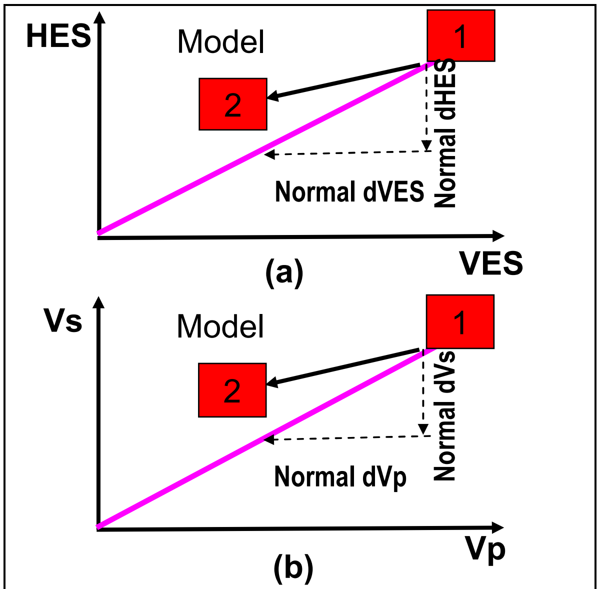

Figure 1: When subsurface stresses change according to VES-HES trend [pink line on (a)] then Vp-Vs remains on a linear trend [pink line on (b)]. In a "high-HES" scenario horizontal stress experiences lesser decline than predicted by a stress trend (a). Then resulting point on Vp-Vs space moves upward from trend line (b).

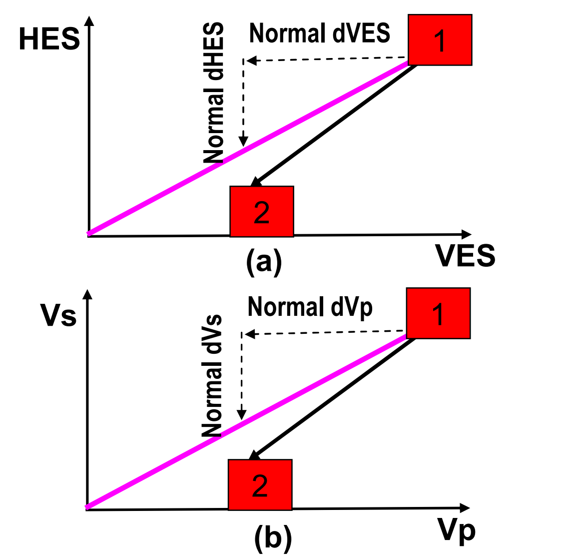

Figure 2: In a "low-HES" scenario horizontal stress experiences larger decrease than expected according to pink trend curve in (a). Then resulting point on Vp-Vs space moves downward below the pink Vp-Vs trend in (b).

Deepwater Gulf of Mexico: prospect 1

Figure 3 shows data points in blue for horizontal and vertical effective stresses along a vertical well drilled down to 20,000 ft below mudline and below 10,000 ft of salt. Total stresses are estimated from 3D finite-element geomechanical modeling while pore pressures are estimated from resistivity logs and calibrated by actual downhole measurements from a modular dynamic tester. The prospect is located in 3151 ft water depth. Immediately sub-salt, we observe very low effective stresses that quickly increase further below salt. These near-salt points clearly fall below the open-basin GOM trend line in red. With increasing stress or increasing distance away from salt, the stresses approach the open basin VES-HES trend.

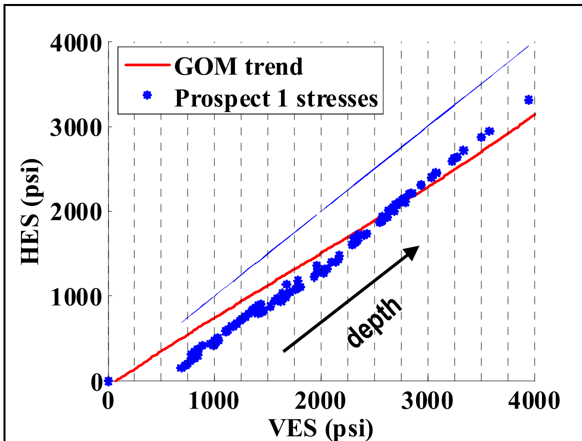

Figure 3: Open-basin trend of effective stresses for deepwater Gulf of Mexico (red line) and estimated stresses from prospect 1 (blue points). Thin blue line shows line of equal stresses (VES=HES).

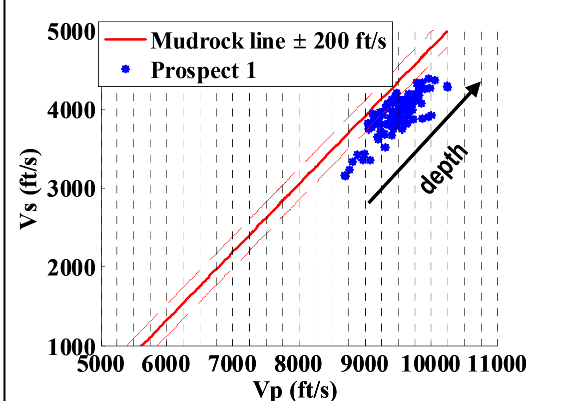

Figure 4: Compressional and shear velocities for sub-salt interval in a vertical well at prospect 1 (in blue) shown with various regressions. Note consistent deviation from the trend immediately sub-salt where both P- and S-velocities are lowest.

Figure 4 shows the corresponding cross-plot of compressional and shear velocities for the same prospect. Sub-salt points with lowest velocity clearly fall well below the Vp-Vs trend. Consistent with the predictions of our rock physics transform both stress and velocity points at this prospect fall below the trend lines. With increasing depth away from salt, the Vp-Vs points approach the GOM mudrock trend line (Figure 4) consistent with the stress behavior depicted in Figure 3. As a separate observation: the estimates of sub-salt effective stresses are extremely low. As velocities are still relatively high one may infer that effective stress was only reduced at a later stage of burial of the sediments.

Deepwater Gulf of Mexico: prospect 2

A similar Vp-Vs anomaly below salt is seen at prospect 2 and it also correlates well with the abnormal VES-HES behavior estimated from geomechanical modeling (Figure 5 and Figure 6). This prospect is also located at approximately the same depth as prospect 1, below ~ 10,000 ft of salt and is also characterized by overpressures and low horizontal stresses. Similar to the first prospect, the data immediately below salt with the lowest estimated stresses and velocities plot below the trend lines, while at greater depth this deviation diminishes and approaches the trend line (Figure 5 and Figure 6).

Compressional settings

Applying the same logic, we predict that Vp-Vs trends in tectonic or compressional basins would likely be shifted "above" the extensional mudrock line, provided the stress field is still active or the stress signature has been frozen in the rock.

Where shear wave splitting occurs (e.g. Boness and Zoback, 2006), the Vp/Vs based on Vs measurements with polarization direction in line with maximum stress would plot above the Vp/Vs trend based on Vs measurements in the orthogonal direction.

Conclusions

The existence of a robust Vp-Vs trend implies that vertical and horizontal effective stresses cannot deviate very much from a quite stable basin-wide relationship. Local deviations from such a basin-wide relationship between horizontal and vertical effective stresses may cause deviations from the established Vp-Vs trends.

We formulate a relation that connects the velocity (Vp-Vs) and the stress (VES-HES) domains and which is consistent with the majority of the measurements. We have tested our predictions and found signatures of anomalous Vp-Vs behavior on several datasets for which stress conditions are known or believed to be "anomalous", deviating substantially from the established "normal" relationships.

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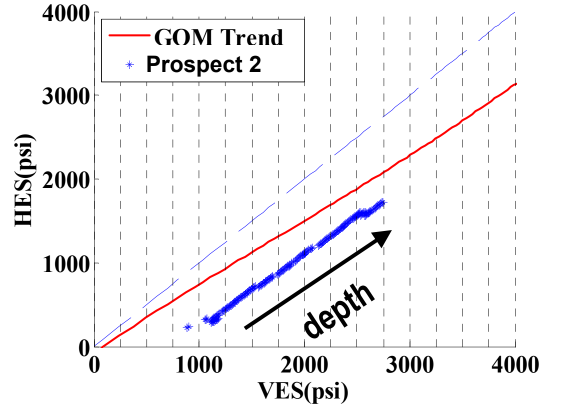

Figure 5: Estimated vertical and minimum horizontal effective stresses in sub-salt interval at prospect 2 (blue points) with the open basin trend (red line). The blue dashed line represents the VES=HES line. The effective stress at propsect 2 is obtained by subtracting the pore pressure from the total stresses estimated with 3D geomechanical modeling.

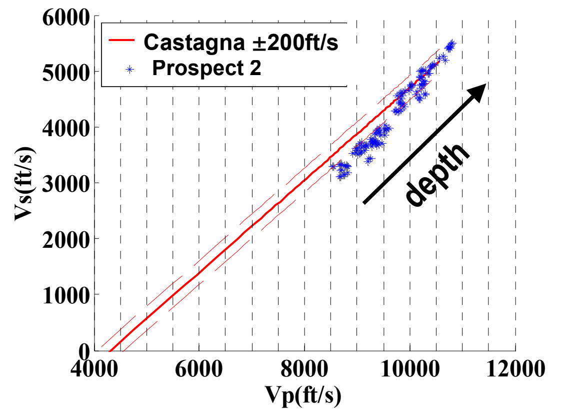

Figure 6: Compressional and shear velocities in mudrocks (blue) at prospect 2 (Gulf of Mexico) together with the Vp-Vs trend derived for the open basin (red).

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EDITED REFERENCES

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