ROLE OF ASSOCIATED MINERALS AND POROSITY IN VP-VS RESPONSE FOR SANDSTONE AND LIMESTONE

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ABSTRACT
Acoustic velocities have known alliance with porosity and lithology. It in turn has bearing with rock aspect ratio. In dry frame condition, for clean formation, aspect ratio can be standardized upon knowledge of lithology, and a semi-empirical Vp-Vs relation can be adopted easily. The dry frame velocity-stress sensitivity is also expected to follow some correlative patterns for compressional and shear velocities as both are incited by pressure induced impact on micro-pore. The presence of associated clay mineral additionally influences the sonic response. It changes the aspect ratio, affects matrix properties due to mineral inclusions, and a conventional dry frame Vp-Vs relation no longer holds good.

The present study investigates inter-relation between Vp and Vs in context to varying porosity, associated minerals and pressure, with an objective to determine dry frame Vp under logging conditions. This has been achieved utilizing a quality core database. Study establishes a pragmatic link between acoustic velocities that is independent of multiple pressure conditions, and is useful for field application. Analysis concludes that velocities can be related through systematized semi-empirical laws, which is independent of formation pressure. Earlier reported empiric themes tend to predict velocities using functions that involve varying constants under different pressure and clay regimes. New observations on studied core data bring congruency in varying conditions and yield a perspective that compares better with available scheme.

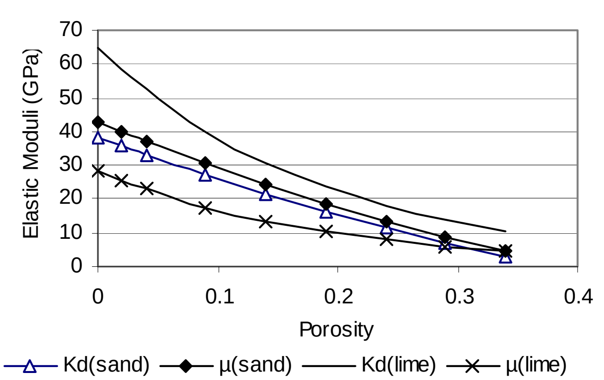

Figure 1.Porosity influence on dry frame moduli for clean sandstone and limestone formation [1, 2]

INTRODUCTION
Sonic velocities in complex formation are of practical importance as clean formations are rarely found. Wet velocities are known through logging tool but dry frame velocities remain unknown, in the presence of associated mineral. It has direct bearing in the application of Biot-Gassmann theory, sanding analysis and sonic concepts.

Shear and Bulk acoustic properties are commonly known to have a

compromising response on many fronts, for homogenous formation. In sandstone, standard Kd (Dry frame bulk modulus) and μ (Dry frame shear modulus) response with porosity are almost similar for a large porosity range of 10-28% at 50MPa pressure (Figure 1). Kd/μ is very close to 0.95 over this wide porosity range [1]. In limestone, similar correspondence exists but Kd/μ ratio varies with porosity [2].
The independent estimation of acoustic velocity is a more tedious subject in complex formation, as effects of micro-pores, pressure and mineral distribution are to be incorporated separately. The existing sonic literature suggests that micro-pore and pressure influence commonly affects shear velocity (Vs) and compressional velocity (Vp). Thus a relative change of Vp versus Vs may compensate for these properties. It opens the possibility of an investigation where the combined influence of porosity and associated minerals can be linked to relative variations in sonic velocities and a generalized Vp-Vs relation is established. Such results are reported earlier for silicates [3] and can be inferred for other combinations from reported multiple relations [4, 5]. Present study explores possibility where velocities can be linked to the petrophysical variables, such that the inter relation is independent of pressure. A quality database is re-examined for this purpose. The approach is confined to estimate dry frame Vp.

STUDY DESCRIPTION

Sandstone

Study reviews 69 dry sample core data of Han (1986) [4]. Samples depict variety of clay material and compaction, from different wells and quarries. Used acoustic data has 1-2% measurement accuracy. All clays and associated minerals are combined within 'clay' term. Wide variations in porosity (0.04-0.30) and clay (0.03-0.30) are present in the dataset. Few sample with very high clay (0.5>Vcl>0.3) are also incorporated. Measurements are made at 40MPa confining pressure. Data suggests an approximate linear Vp-Vs relationship, with scatter. It is observed that ratio of clay volume and porosity is playing role in Vp-Vs inter-relation. This ratio is henceforth termed as 'clapor' in subsequent discussion. A high clapor is found to associate with high scatter in a linear Vp-Vs relation.

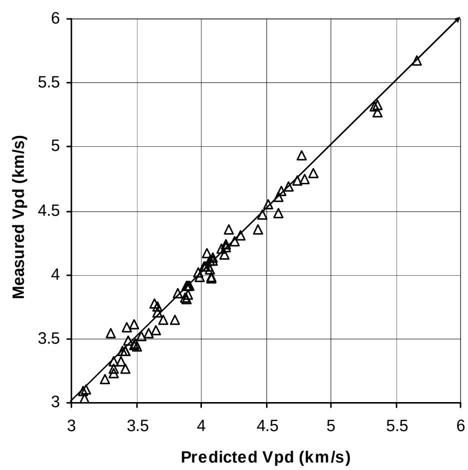

Figure2. Predicted Vpd versus Observed Vpd

To understand the role of clapor, a multivariate analysis is conducted between Vp, Vs and clapor. It provides an excellent linear correspondence between these variables with coefficient of correlation 0.98 and suggests a dry frame Vp-Vs relation as below:

$$V_p = 1.3719\ V_s - 0.0137\left(V_{cl}/\phi\right)^{1.5} + 0.4718 \qquad (1)$$

The equation above introduces clapor effect. The clapor term gains significance with increasing Vcl and lower ϕ content. It puts the available data in better perspective and predicts Vp response with high accuracy as shown in Fig.2. For clean sandstone close to matrix (Vs = 4.11km/s), Eq.(1) suggests a Vp/Vs value of 1.486 and predicts Kd/μ ratio of 0.88. These are consistent with theoretical values. For a clean sand (ϕ=0.2, dryVs = 2.8km/s), Vp/Vs changes to 1.53 while Kd/μ moves close to 1.03. These implications are consistent with other observations on clean sand [1] that put Kd/μ close to 1.0. With increasing clay, the clapor related term tends to reduce Vp, but Vs reduces more drastically that consequently results a gradual increase in Vp/Vs with clay, which is a known fact.

A comparison is made between Vp(dry) estimates made currently with earlier suggested and commonly utilized semi-empirical laws of Han [4] and Vernik [5]. Results show a better representation of Vp(dry) in the new relationship (Fig.3). However it is emphasized that there is a difference in approach. In earlier methods Vp(dry) is estimated independently through porosity and clay, while in the current estimate it incorporates additional Vs information. In waveform logging Vs is available and it is practical to work on the new proposition.

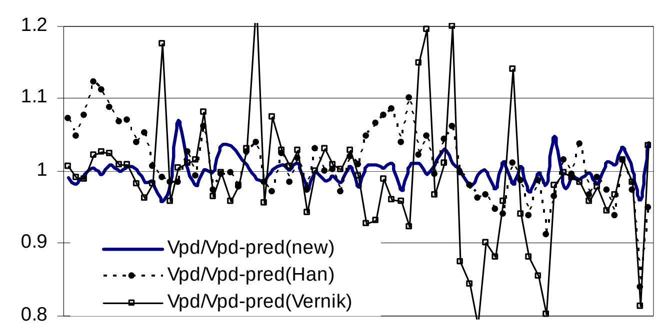

Figure3. Comparison of Vpd with other empiric theme

Verification

Two different core data sets are used for this purpose. Firstly a multi-pressure core data on Troll sands (Blangy *el al.,* 1992) [6] is utilized. Dry core acoustic measurements are made on 38 core samples at different confining pressure of 30MPa to 5MPa. A total of 226 measurements are included in this dataset. All minerals other than quartz are combined within 'clay' term. The computed Vcl varies within 0.21-0.5 values, while porosity ranges 0.22-0.37. Vp(dry) is re-computed through Eq.1 and are compared with available data in Fig.4. There is a slight difference here; the intercept value in Eq.1 is 0.318, instead of 0.4718. A very low error percentage (≤ 4%) is mostly observed. The high error is present only for samples having high porosity (>0.33) or/and high clay (>0.35) at 10MPa and 5MPa pressure. At these effective pressures,

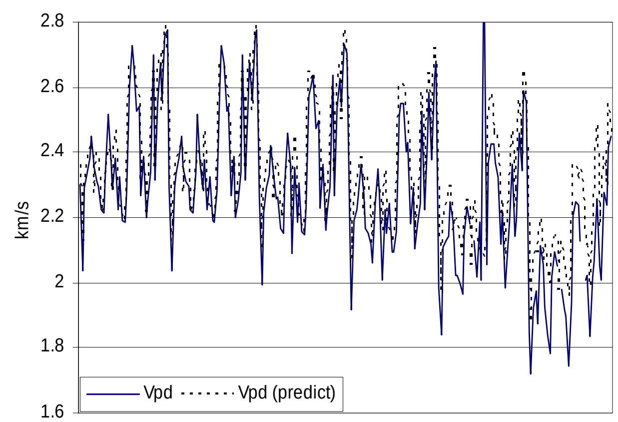

Figure 4.Verification with Troll sand core data [6]

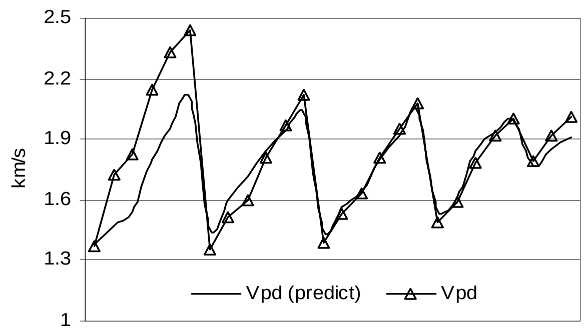

Figure5. Verification with synthetic shaly sand core [7]

poorly consolidated samples are expected at high porosity. A benchmarking for pressure (>10MPa), porosity (<0.33) and clay fraction (<0.33) can be easily set in this dataset for accurate velocity prediction. In view of the measurements accuracy (2 %), the depicted 4% error in Fig.4 is reasonable.

Additional verification is done through a data set of synthetic samples created by mixture of clean sand and Kaolinite [7]. Acoustic and petrographic measurements are made at different confining pressures (5-50MPa). The selected samples are within the pressure, porosity and clay limit as set in earlier verification. The used intercept in Eq.1 is 0.28. Dry Vp is calculated and result is shown in Fig.5. It represents a reasonable estimation, except for first few points. These points are significantly identified by original work as clay supported points [7] and do not represent the sand supported frame. It may be noted that plotted data is a multi-pressure (≥10MPa) data.

Limestone

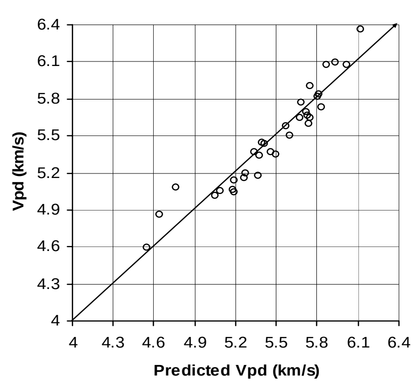

Figure6. Vpd prediction for dolomitic-lime

A detailed 90 samples carbonate core study of Rafavich *et al.* (1984) [8], from four different wells is used here. Two wells are used for benchmarking while other are used for verification. Carbonate facies vary from total calcite to total dolomite. Porosities vary from 0.02 to 0.18.

Two separate data sets are created, one for dolomitic limestone (33 samples) and the second for calcitic dolomite (25 samples), based on mineral content. All minerals, other than calcite, are added within 'clay' term for dolomitic limestone case. Dolomite is the primary associated mineral here. Similarly calcite is added within 'clay' term for calcitic dolomite sample-set. Both datasets are analyzed separately.

A multi-regression analysis for relative Vp-Vs variations in dolomitic lime, again suggest the utilization of Clapor (Vcl/Phi) term. The excellent correspondence, with correlation coefficient of 0.9, shows the velocity relationship for dry Vp as below:

$$V_p = 2.279\ V_s - 0.005\left(V_{cl}/\phi\right) - 1.5943 \qquad (2)$$

Vp(dry) prediction through Eq.2 is plotted in Fig.6. The Eq.2 suggests a gradual Vp/Vs decrease with increasing clapor. As Vp/Vs for other major associated minerals are lower compared to calcite, it is understandable. It also puts a Vp/Vs value of 1.81 for clean calcite matrix (Vs = 3.43km/s). It is very close to theoretical value of 1.8. Vp/Vs changes to 1.54 for clean arenite with 20% porosity (Vsd ~2.15km/s). Such porosity dependent Vp/Vs is consistent with earlier results [2]. A multi-regression analysis for calcitic dolomite dataset (25 samples), demonstrates a linear Vp-Vs relationship with relatively poor correlation coefficient (0.81) as below,

$$V_p = 1.6312\ V_s + 0.0074\left(V_{cl}/\phi\right) + 0.587 \qquad (3)$$

Vp/Vs value becomes 1.78 for dolomite matrix (Vs=3.9km/s). For dolomite with 17% porosity (Vs~2.83km/s), Vp/Vs moves to 1.83. These are consistent with standard [9].

Verification

The proposed relation for calcitic dolomite and dolomitic lime are tested with another 22 sample of carbonate data compiled from two different wells; those are also part of same core study. Porosity varies as 0.02-.18, while lithology ranges from clean calcite to clean dolomite. Few data points are removed where porosity falls below 0.02 or anhydride becomes predominant in matrix part. For dolomitic lime and calcitic dolomite, dolomite and calcite content are predominant 'clay' respectively. All other associated minerals (anhydrite and quartz) are also clubbed within 'clay'. Eq. (2) and Eq. (3) are accordingly applied to predict dry Vp. The computed Vp closely matches with measured velocities (Fig.7). Observed error is mostly lower than 4%, in a 22-sample dataset. Although results provide reasonable verification, another big carbonate data may be required to give further strength to observations.

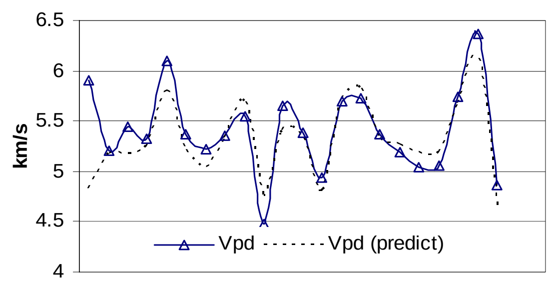

Figure7. Verification for dolomitic-lime and calcitic dolomite

Siliceous limestone

Core study of Wilkens *et al.* (1984) [10] is used for present work. Acoustic measurements are made on 13 sample core data at varying confining pressure (0.01-2.0kbar). Samples have predominant limestone lithology with silica as associated mineral. Samples with predominant silica (>50%) are removed from dataset. Porosity varies between 0.02 to 0.068 fractions. A multi-regression analysis shows the presence of Vp-Vs relation (correlation coefficient 0.85) as,

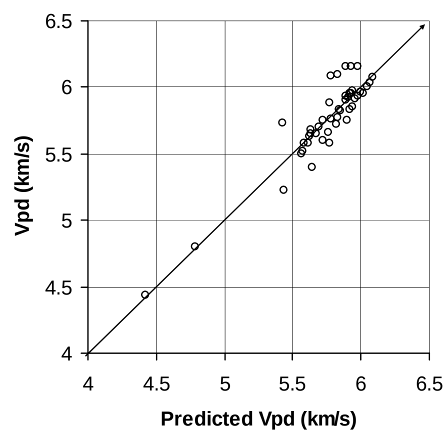

Figure8. Predicted Vpd versus Observed Vpd

$$V_p = 1.8458\ V_s - 0.0417\left(V_{cl}/\phi\right) + 0.36 \qquad (4)$$

Regression analysis is shown in Fig.8. Although we do not have another similar dataset to validate the relation, Eq.4 puts forward the point successfully that pressure independent dry frame Vp-Vs relations can be adopted under varying lithology.

DISCUSSION AND CONCLUSIONS

Study delivers an important implication that the type of associated mineral does not govern the relative Vp-Vs changes, as long as basic lithology remains unchanged. Vp or Vs independently may be different in varying associated mineral volumes.

Under different lithology, dry frame Vp can be predicted from dry frame shear velocity, porosity and clay inputs with good precision. For practical purposes, all associated minerals can be clubbed under a general clay term. Excellent Vp-Vs relations are observed for shaly sand, dolomitic-lime, calcitic dolomite and siliceous lime, when associated minerals are supported within primary matrix.

Pressure variations do not affect the dry frame Vp-Vs relations, as verification process incorporates multi-pressure data. Changing Vs with pressure seems to compensate for pressure effect on Vp in new relation. Fracture presence may be one of the exceptions.

Ratio of associated mineral volume and porosity fraction plays an important role in proposed relations. Study presents the scope for similar relations for other lithology with minor changes.

Study is in consonance with earlier reported dry frame Vp/Vs and Kd/μ ratios, for clean sandstone, calcite and dolomite. The utility of study should be viewed within set petrographic limits. Relationships may not serve similar success for formation with high porosity, high clay, and very low confining pressure.

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