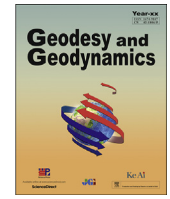
Geodesy and Geodynamics xxx (2017) 1–5

Contents lists available at ScienceDirect

Geodesy and Geodynamics

journal homepages: www.keaipublishing.com/en/journals/geog; http://www.jgg09.com/jweb_ddcl_en/EN/volumn/home.shtml



Q1 # Petrophysical relationship for density prediction using *Vp* & *Vs* in Meyal oilfield, Potwar sub-basin, Pakistan

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A R T I C L E I N F O

Article history:
Received 30 January 2017
Accepted 30 July 2017
Available online xxx

Keywords:
Shale
Gardner
Potwar
Carbonates
S-Waves

A B S T R A C T

Conventional petrophysical investigations are based on P-wave seismic velocity analysis to predict density information, while ignoring the important S-wave velocity. This study is based on S-wave velocity analysis of density estimation of Meyal Oil Field (Potwar Plateau, Pakistan), which reveals a very high correlation ($R = 0.87$) between predicted and actual density. Since the availability of S-wave velocity (*Vs*) data increases, it's highly appreciable to take into account the contribution of *Vs* in improvement of density estimates. This investigation only focuses on driving new constants ($a = 1.92$ and $b = 0.186$) for Gardner's relationship to estimate density of pure carbonates (*Vsh*< 10%) in the study area, where the traditional model gave poorer density predictions. The proposed empirical expression with locally extracted unknowns from well log data proved its ability in terms of density prediction (showing very close agreement with measured densities) and best fitting the datasets at low as well as high density values when compared with Gardner's equation. Based on our analysis, the exploratory study neither intends to replace the well established density estimation models nor to extend information over what information can possibly be extractable from *Vp*. However, our research does stimulate the growing use of *Vs* and importance of local unknown constants especially in carbonates reservoir interval to avoid misuse of most widely used Gardner relation in all geological settings.

Q4 ## 1. Introduction

It is crucial to estimate the relation between sonic velocity in sediments and rock lithology for interpreting seismic reflection data or from geophysical well logs of sedimentary sequences, knowledge of reliable relationships between velocity and other key petrophysical parameters, such as porosity or density, are essential for calculating impedance models for generating synthetic seismic data [1,2] such correlations are also applied to identify the origin of reflectivity patterns on seismic reflection sections [3,4]. Thus, sonic velocity is an important parameter for correlating lithological and geophysical signatures. The most popular formulations extensively used in rock physics [5,6] which describe sonic wave propagation in porous media are hard to apply to pure carbonates representing complex system due to their variety of unique digenetic rock fabrics with specific elastic properties. Generally three parameters (density, P-wave velocity and S-wave velocity) are extracted from wire line data for petrophysical analysis. The velocities (*Vp* and *Vs*) are measured in the laboratory where core samples are available which is not the most often case due to budget limitations and required testing facilities. These are key petrophysical parameters for reservoir characterization and commonly used to study the velocity anisotropy which is subsequently associated with estimation of the pore fluid phase, micro crack density and compaction [7,8]. Also acoustic impedance is the product of velocity and density which is

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Peer review under responsibility of Institute of Seismology, China Earthquake Administration.

ELSEVIER Production and Hosting by Elsevier on behalf of KeAi

https://doi.org/10.1016/j.geog.2017.07.008

another important parameter in seismic reflection work indirectly derived from the seismic velocity information obtained from well logs. When information about density is unavailable, it is often predicted from P-wave velocity (*Vp*) by Gardner's relationship [9]. The results of his work are summarized in graph shown in Fig. 1. The dotted line represents the predictions from Equation (1) and the dashed lines show constant acoustic impedance (see Table 1).

$$\rho = 1.74(Vp)^{0.25} \quad (1)$$

where ρ = bulk density in g/cm^3 and *Vp* = P-wave velocity in km/s.

A change in rock composition cannot be simulated very satisfactorily in the laboratory. Consequently no well established relations are possible between different specific acoustic parameters. In this study we are looking for an empirical expression that might applicable satisfactorily for an interval within pure carbonate unit of Chorgali formation. The carbonates are more susceptible for digenetic and other changes in such type of geological environment than other lithologies like siliciclastic [11].

1.1. Study area

Study area lies in the Potwar sub basin, which is one of the oldest oil provinces of the world, where first commercial discovery from the Himalayan Fordland was made in Potwar sub-basin at Khaur in 1914. The sub-basin hosts multiple structural leads as interpreted Moghal et al. [12]. So for 150 exploratory wells have been drilled. The occurrence of hydrocarbon in various parts may be related to varying structural styles divided into pop-up anticline, triangle zones, snake-headed anticline and salt cored anticlines.

The Cambrian, Permian, Jurassic, Paleocene and Eocene formations are producing oil in the area. In Meyal Chorgali and Datta Formations are major oil producing reservoirs. The Sakesar limestone is light yellow gray, massive and partly dolomitized and locally contains chert concretions. The Chorgali Formation is creamy yellow to yellow gray, silty, partly dolomitic and thin bedded limestone [13].

The detailed stratigraphic studies, the oil wells drilled across the Salt Range-Potwar Foreland Basin (SRPFB) and the Jehlum Plain have led to an understanding of the area's stratigraphy with the help of Fig. 2 as mentioned by Fatmi et al. [14].

2. Results and discussion

In a complex tectonic setting, it is likely that Chorgali carbonates might have undergone diagenetic changes, that occur far more quickly than compaction, which causes a special seismic velocity (*Vp* or *Vs*) distribution in Potwar sub-basin foreland carbonates and

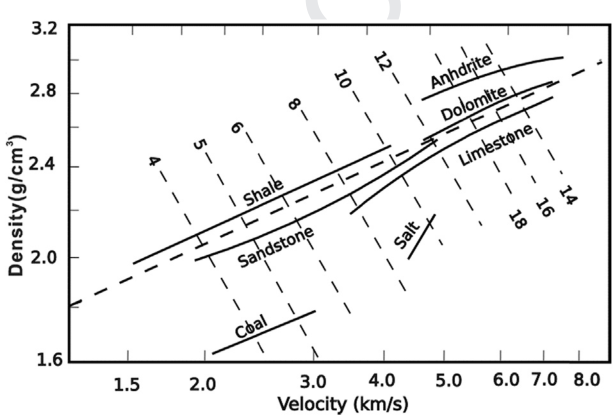

Fig. 1. Relationship between P-wave velocity's and density for various lithologies [10] (from Sheriff and Geldart 1995).

Table 1
Zonation on the bases of percentage of shale volume.

Vsh (%)	Zone
<10	Clean zone
10 to 35	Shaly zone
>35	Shale zone

complicates velocity estimations. Lithology, porosity, age, burial depth and clay content might affect the density prediction. All these factors lead to poor direct correlation between acoustic properties such as *Vp* and *Vs*. Therefore, it is necessary to modify the commonly used correlations like "Gardner's relation" (*Vp*-density) or the "time-average-equation" (*Vp*-porosity) before being applied to carbonates. We have used Gardner law as basic framework to conduct the research which is basically an approximate average of the fits for shale, sandstone and carbonates. Our main objective is to develop an empirical relation of the form of Equation (1) only for the reservoir interval (clean carbonates) with volume of shale less than 10% instead of whole Chorgali formation as Gardner's did for carbonates generally.

There are many techniques (gamma ray log, the resistivity log, and the density-neutron logs) available to calculate the shale volume, but for the present study gamma ray log is used because it is one of the best methods used for identifying and determining the volume of shale. The Gamma-ray index is calculated by using the equation developed by given by Dresser Atlas [15]. Its mathematical definition is.

$$IGR = (GR\log - GR\min)/(GR\max - GR\min)$$

where, IGR is the Gamma-ray index, GRlog is the Gamma-ray reading for each zone and GRmin and GRmax are the minimum Gamma-ray value (clean sand or carbonate) and the maximum Gamma ray value (shale).

The shale volume can be calculated from the Gamma-ray index, by using the following formula developed by Fakhry [16]. Its mathematical representation is given below:

$$V\text{sh} = 0.33[2 \times (2IGR) - 1.0]$$

The different zones are classified into clean, shaly and shale zones according on the basis of volume of shale by using approach Ghorab [17].

In the Chorgali Formation clean zone (3770 m–3834 m) containing Vsh < 10% is distinguished clearly from shale zone (3760 m–3766 m) with Vsh > 35% on basis of volume of shale percentage as shown in Fig. 3 (see Fig. 4).

Traditionally, P-wave seismic velocity is known as best candidate to estimate density as well as S-wave velocity information. However, the current work also focuses to incorporate the S-wave velocity (*Vs*) for density estimates keeping in view the increasing availability and tendency towards its use. First the measured density values are plotted against the *Vp* and a relation is derived from this dataset which is given by

$$\rho = 1.92 \times Vp^{0.186} \quad (2)$$

When density values computed by Gardner's relation are compared with the actual density values it was found that it did have difficulty while prediction because of very low value of correlation coefficient (R = 0.45), however proposed equation provided us with R = 0.90 showing close approximation with measured density as shown in Fig. 5 and Fig. 6. Conventionally P-wave velocity (Vp) is used for density prediction but here an

Please cite this article in press as: G. Akhter, et al., Petrophysical relationship for density prediction using *Vp* & *Vs* in Meyal oilfield, Potwar sub-basin, Pakistan, Geodesy and Geodynamics (2017), https://doi.org/10.1016/j.geog.2017.07.008