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Research paper

Acoustic properties in travertines and their relation to porosity and pore types

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ABSTRACT

Sonic velocities of Pleistocene travertines were measured under variable confining pressures. Combined with petrographical characteristics and petrophysical data, i.e. porosity, permeability and density, it was determined that travertine porosity, pore types and cementation control compressional-wave (V_p) and shear-wave velocity (V_s). At 40 MPa confining pressures, V_p ranges between 3695 and 6097 m/s and V_s between 2037 and 3140 m/s. Velocity variations in travertines are, as with all carbonates, primarily linked to sample heterogeneity, i.e. differences in fabric, texture and porosity. They thus not necessarily emanate from changes in mineralogy or composition. Body wave velocities have a positive correlation with sample density and an inverse correlation with porosity. The travertines, sampled in extensional settings with normal faulting activity, define a specific compressional-wave velocity (y-axis) versus porosity (x-axis) equation, i.e. ($\log(y) = -0.0048x + 3.7844$) that differs from the V_p-porosity paths defined by marine carbonates. Acoustic wave velocities are higher for travertines than for marine carbonates. Travertine precipitates form rigid rock frames, often called framestone, with large primary pores. Marine carbonates on the other hand often consist of (cemented) transported sediments, resulting in a rock frame that permits slower wave propagation when compared to the continental limestones.

Acoustic velocity variations are linked to variations in pore types. Mouldic pores (macropores) show faster wave propagation than expected from their total porosities. Microporosity, interlaminar and interpeloidal porosity result in slower acoustic velocities. Framework pores and micro-moulds are associated with lowered acoustic velocities, while vug porosity is found above, on and below the general velocity-porosity trend. Not only the pore type, but also pore shapes exert control on body wave velocities. Cuboid-and rod-like pore shapes increase the velocity, while plate-and blade-like pore shapes have a negative effect on the velocity. The study demonstrates how seismic sections in travertine systems can contain seismic reflections that are not caused by non-carbonate intercalations, but relate to geobody boundaries, in which the seismic expression is function of porosity, pore types and shapes. This study provides and relates petrophysical data, i.e. porosity, permeability and acoustic velocities of travertines and is of importance for the interpretation of seismic reflection data in subsurface continental carbonate reservoirs.

1. Introduction

Carbonate deposits gained interest due to their potential as reservoir rocks, e.g. the supergiant fields in the Middle East (Nurmi and Standen, 1997) and offshore Brazil (Thompson and Oftebro, 2011; Wright, 2012). The genesis of continental carbonates is associated with physico-chemical and biological precipitation that

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largely influences the rock texture and petrophysical properties (Toumelin et al., 2003). This causes petrophysical heterogeneity that can become even more pronounced due to diagenetic overprinting (with cementation, dissolution, recrystallisation, dolomitisation, fracturing, etc.). The studied continental carbonates in Turkey and Hungary are calcareous spring deposits, i.e. travertines (Pentecost, 2005), associated with ambient and hydrothermal fluids (El Desouky et al., 2014; Sierralta et al., 2010). Their deposition is controlled by a complex interplay of physico-chemical, biological and hydrological factors, including CO_2 degassing, the dominating process for travertine precipitation (Fouke, 2011; Guo and Riding, 1998; Kele et al., 2011; Özkul et al., 2013, 2014; Pentecost, 2005). Travertines can form in a thin water film in subaerial conditions, or in lake, marsh and fluvial environments. These precipitates have been widely studied (Alonso-Zarza and Tanner, 2010; Ford and Pedley, 1996; Pedley and Rogerson, 2010; Pentecost, 2005), however, a detailed investigation of the rock petrophysics was seldom accomplished. This paper aims to investigate the behaviour of acoustic waves in travertines.

The dependency of sonic velocities on lithology, rock texture and fabric is the key to understand acoustic logs and seismic sections in sedimentary systems. Compressional-wave velocity and bulk density are used to calculate acoustic impedance. In carbonate lithologies that consist purely of calcite, grain density variations are limited, meaning that other parameters cause variations in body wave velocity. These parameters are of importance for the interpretation of seismic reflection and geophysical data. The control that is exhibited by porosity on acoustic velocity was already reported in the late fifties (Biot, 1956; Gassmann, 1951). Causes for velocity variations in pure carbonates were part of several studies especially from the early nineties onwards. It was concluded that not only porosity, but also the entire rock fabric and its texture are of importance (Anselmetti and Eberli, 1993; Wang et al., 1991). Moreover, carbonates are prone to diagenesis, which can easily alter porosity, crystal morphology, the rigidity of the solid framework, etc. (Anselmetti and Eberli, 1993; Braaksma et al., 2003; Verwer et al., 2008).

In this study, compressional-wave velocity (V_p) and shear-wave velocity (V_s) are measured on travertine samples from three different locations, under confining pressures that approach in situ subsurface conditions. Sonic velocity measurements were done in combination with petrography, X-Ray Diffraction (XRD) and micro-Computer Tomography (μCT) analyses.

2. Geological setting

The selected dataset of Quaternary travertines is assembled from quarries near Denizli, in Turkey (Özkul et al., 2013) and from Süttő (Bakacsi et al., 1994; Sierralta et al., 2010) and Budakalász (Kele et al., 2003) in Hungary.

The Denizli Basin (Western Turkey) is a Neogene-Quaternary depression, of 70 by 50 km. The basin is the continuation of the E–W-trending Büyük Menderes Graben and the NW–SE-trending Gediz Graben (Bozkurt and Bozkurt, 2009; Gürer and Yilmaz, 2002; Kele et al., 2011; Özkul et al., 2002, 2013). The Quaternary deposits are subdivided in the Tosunlar Formation, with alternating conglomerate, sand- and mudstone deposits, and alluvial fans of the uppermost Quaternary. The alluvium strata are associated with travertines (Alçiçek et al., 2007). The travertine deposits examined in this study are situated in the Ballık area, at the junction of the locally E–W-trending Denizli Graben and the adjacent NW–SE-trending Baklan Graben (Gürbüz et al., 2012; Van Noten et al., 2013). The sampling location for this study is the Alimoğlu quarry.

The Transdanubian Range (TR) is a horst structure in the Pannonian Basin, Hungary (Dolton, 2006; Haas, 2012). The Buda Mountains and Gerecse Hills crop out along the Danube River. They are part of the Transdanubian Range and are mainly comprised of Mesozoic carbonates, which are covered by Cenozoic clastic and carbonate sequences. The terrace region of the Danube River is characterised by alluvial deposits (sand and gravel), but often travertine precipitates exist. The Budakalász and Süttő travertines, respectively from the Buda Mountains and Gerecse Hills are examples of deposits that cover geomorphic steps (terraces) of the Danube River.

Travertines (including the world heritage site of Pamukkale) are known to occur along basin bounding normal faults. Meteoric water infiltrates along topographically elevated areas, such as horst structures (Mehmet Özkul et al., 2013). Above average geothermal gradients, associated with extensional settings and volcanic activity, are two important factors steering infiltrated and thermal waters. Meteoric water can mix with for example karstic water, and form corrosive fluids that enhance carbonate dissolution. Strontium isotope analyses, both on bulk samples and crystalline cement bands have shown that the Lycian nappes (Mesozoic) are a likely candidate as source rock in the Ballık area (El Desouky et al., 2014; Gündoğan et al., 2008; Kele et al., 2011). Surfacing along normal faults of CO_2-rich, thermal fluids results in the precipitation of travertines (Goldscheider et al., 2010; Nador, 1993; Sierralta et al., 2010).

3. Methodology

The petrophysical measurements are conducted on sixty 1.5-inch (3.81 cm) diameter plugs. The effective porosity in the plugs is measured by means of helium expansion porosimetry. Gas permeability, in this case with nitrogen gas (N_2), is measured in a steady state permeameter.

XRD analyses were conducted on 10 representative samples to confirm that travertines in Denizli and from Süttő and Budakalász are composed for well over 90% of calcite, as previously stated in several studies (Kele, 2009; Kele et al., 2011; Khatib et al., 2014; Özkul et al., 2013; Sierralta et al., 2010). Measurements have been carried out at 45 kV and 30 mA, using Cu-Kα-radiation and a scan speed of 0.010° 2ϑ/s. Diffraction patterns are subsequently compared against mineral patterns of a standard database in the DIFFRAC^{plus}, 2004, EVA software 10.0 rev. 1 (Bruker, 2013). Quantitative analyses are carried out using the Rietveld method, with TOPAS-Academic V4.1 and JEdit V4.2 software packages (Coelho, 2012).

Prior to the sonic velocity analysis, the plugs are dried at 65 °C for at least three days to ensure that all water is removed from the samples. Even small amounts of water could significantly lower the elastic shear moduli and give cause to erroneous analyses data (Mavko et al., 2009). Next, samples are left to equilibrate for 48 h at room temperature and humidity conditions (19–21 °C, 50–60%). Ultrasonic compressional-wave velocity (V_p) and shear-wave velocity (V_s) are measured with a High Pressure (ultrasonic) Measurement System (HPMS), as function of the applied confining pressure with a transducer arrangement (VerdeGeoscience©, Vermont, U.S.A.) that propagates one compressional and two independent and orthogonally shear waves (V_s1 and V_s2) along the core axis. The orthogonal shear-waves are averaged to produce a homogeneous shear-wave velocity. The experimental setup contains a source and receiver crystal. The source crystal is excited by a fast rise time electrical voltage pulse, producing a sonic pulse with a frequency of 1 MHz. The receiver crystal records the flight-time of the first arriving wave front of the sonic pulse (García-del-Cura et al., 2012).

Acoustic velocities are obtained by measuring the one-way travel time along the sample axis divided by the sample length. The arrival time is picked when the signal exceeds a threshold of the first three half-cycles of the signal. The error range of the ultrasonic velocity measurements falls within 3%. The measurements were conducted at confining pressures of 2.5, 5, 10, 20 and 40 MPa in a hysteresis loop.