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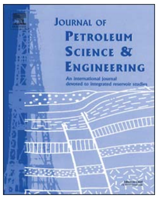

A new method for rock brittleness evaluation in tight oil formation from conventional logs and petrophysical data

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ABSTRACT

Brittleness is a critical indicator for hydraulic fracturing candidate screening in unconventional reservoirs. Current rock brittleness estimation models are often inferred from mechanical parameters and mineralogical data, which primarily use empirical equations. However, the absence of shear sonic velocity data and insufficient mineral data sometimes restricts its wide application. In this article, our objective is to illustrate the application of a data-driven approach for rock brittleness estimation that employs computational intelligence technologies (multilayer perception and radial basis function models) that use conventional well logs as inputs. To reflect the local rock type variation with depth, we first updated the typical mineralogy based brittleness calculation formulas. A database of the well logs, mechanical parameters, X-ray diffraction (XRD) and QEMSCAN mineralogy results collected from a single well in the Santanghu tight oil formation in the Xinjiang basin, China was then constructed. Rock brittleness tests were performed using a multilayer perception model and radial basis function model with different inputs. The comparison of the rock brittleness results produced by the log-based soft computing technologies, mechanical-based method and mineralogy-based method demonstrated that the data-driven approach is flexible and has sufficient accuracy. According to the performance indicators, the predictive performance of the radial basis function model was found to be better than that of the multilayer perception model. This study shows that soft computing technologies can be used to infer missing data when the mineralogical data are inadequate and are less dependent on acoustic full-wave logging, and they are therefore more applicable and practical than traditional empirical formulas.

1. Introduction

Unconventional reservoirs are becoming a significant contributor to hydrocarbon production across the world. Because the gas flow resistance of unconventional reservoirs is much greater than that of conventional reservoirs, the combination of horizontal drilling and multistage hydraulic fracturing technology is commonly used to enhance hydrocarbon production by creating efficient complex fracture networks (Cipolla et al., 2008; Chong et al., 2010). Previous reports have shown that the successful creation of a complex fracture network is related to increased rock brittleness. Therefore, rock brittleness is usually regarded as an important mechanical parameter when describing formations that are likely to generate complex fracture networks under hydraulic fracturing. Although researchers have performed many studies on brittleness, there is still no universal definition and applicable standard for brittleness evaluation because of different physical sources. Rock brittleness can be calculated using stress-stain curves obtained from triaxial measurements, including the ratio of the elastic strain and total strain, the ratio of the compressive to tensile strengths, friction angle, Brinell hardness, axial point load, and empirical equations that involve stress and strain (Hucka et al., 1974; Altindag et al., 2004; Li et al., 2013; Heidari et al., 2014; Zhou et al., 2014; Kias et al., 2015). However, it is not feasible to evaluate rock brittleness using triaxial laboratory measurements due to the limitations of intact samples and expense. Brittleness estimates employing mineralogical analyses and well logs are more practical because the information is more easily and cheaply gathered from laboratory and downhole measurements than from mechanical tests.

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Those attempts to estimate brittleness have had a certain degree of success, but they also have drawbacks. Recently, some authors have tried to build correlations between brittleness and well logs because that data-driven approach is universally applicable and more practical than employing physical equations. Jin et al. (2014a, 2014b) studied the relationships between rock brittleness and well logs and presented a statistical regression analysis of brittleness based on porosity vs. brittleness crossplots and sonic compressional slowness vs. brittleness crossplots. The application of that novel method has enjoyed a certain success in typical U.S shale gas plays (Woodford, Barnett and Eagle ford). Wang et al. (2015) developed a brittleness model using the ratio of gamma rays to photoelectric absorption cross section index (GR/Pe), and they illustrated that brittleness variations can be observed using special well logs alterations along the wellbore because the Pe log can be used to discriminate different brittle minerals. However, because the study area is in the Chang 7 shaly sandstone in the Ordos Basin in China, more studies are needed to validate whether this empirical correlation is only applicable in this basin. In addition, Pe logs are not always available for all wells, which therefore also restricts its wide application.

Because there are complex relationships between brittleness and non-linear and fuzzy well log data, traditional simple regression and multiple-regression methods cannot guarantee enough accuracy, even if those methods are usually easy to apply. Furthermore, in most cases, one major drawback of single-log brittleness estimation is the assumption that no large variations in other parameters exist that can affect the reading of the logs; however, this type of approach heavily depends on independent well logging quality, and, otherwise, substantial errors potentially exist. To offset some of these problems, prediction technologies, such as artificial neural networks, can be utilized for the prediction of rock brittleness. Neural networks are capable of dealing with complicated and unknown multilinear problems, and they are characterized as computational models with particular abilities to adapt, learn, generalize, recognize, cluster and organize data (Huang et al., 2003). In recent years, artificial neural networks have been successfully employed for developing predictive models in many petroleum fields such as sand control, permeability and porosity prediction, drilling optimization, EOR candidate and fracturing candidate optimization (Parada et al., 2012; Obersinkler et al., 2003). The data-driven based features of this modeling approach can provide increased flexibility for self-adjustment to adapt to various ranges of data. As a matter of fact, the prediction of rock brittleness is of a similar nature, but artificial intelligence technologies have not yet been used for rock brittleness in hydrocarbon plays.

The purpose of this study is to outline a data-based approach for brittleness estimation using multi-layer perception (MLP) and radial basis function (RBF) models. Because the quality of the inputs of the computational intelligence models discussed below is critical, establishing a reliable brittleness dataset is the primary step. An initial effort has been made in this study to establish a brittleness dataset for a tight oil formation in the Xinjiang Basin, China, using mineralogical XRD and QEMSCAN analyses. Additional work was performed to assess the possible connections between the material properties and brittleness in terms of the mineralogical contents and elastic parameters from well logs, and therefore more appropriate brittleness calculations can be selected. The development of the new prediction models is discussed in detail, and the outputs of the models are also discussed in this paper. The results from the MLP and RBF models are compared to reveal the efficiency of the prediction processes of the two networks.

2. Materials and methods

2.1. study area

Well H is a pilot well in the Permian Lucaogou Formation of the Santanghu Basin in China. The Santanghu Basin is situated in the Hami area in the NE Xinjiang Uyghur Autonomous Region. It is an NW–SE striking basin that covers an area of 2.3×10^4 km^2. It can be divided into three first-order tectonic units: a northern uplift belt, center depression belt and southern thrust nappe belt. The center depression can be further subdivided into five highs and six sags. The Malang-Tiaohu Sags, which has an area of 3200 km^2, is the primary area for oil and gas exploration and development. The advantages of the Santanghu tight oil are its large thickness (100–300 m), wide distribution and good preservation. In recent years, exploration and production tasks within the Santanghu formation have been performed by PetroChina, and commercial tight oil has been obtained. The promising tight oil prospects in this area are indicated by some appraisal wells. The reservoir has characteristically high brittleness, high oil saturation and high-density oil. The oil in the 2nd member of the Tiaohu Formation is sourced from the Lucaogou high quality source rock underneath. The main migration pathway is faults, and the migration distances range from 100 m to 500 m. The unique tuffite (tuff limestone, pyroclastic and detrital sandstone) reservoir is different from shale, sandstone, and carbonate reservoirs. The accumulation of tight oil in the tuffite is mainly controlled by the distribution and properties of the Lucaogou source rock and tuffite reservoir within the 2nd member of the Tiaohu Formation.

The structures in this study area consist of gentle anticlines showing a north-south general trend. Prior reservoir characterization results show that the TOC content of the hydrocarbon rocks ranges from 0.01% to 18.79%, and the kerogen of the organic matter is predominantly of Types III and II2. The target sedimentary tuffite formations are characterized by porosity of 16.2–21.7%, permeability of 0.0001×10^{-3}–0.500×10^{-3} μm^2, a stable areal distribution of the matrix pore volumes and their constituents, a large variation in the fracture and pore characteristics among the different tectonic regions as well as the different well fields and different intervals in the same tectonic. According to previous studies, the tuffite in the Permian Tiaohu Formation is a fine-grained tight reservoir with high porosity and low permeability. The pore throats are dominated by 88.3% nano-scale pore throats, and the air permeability is less than 0.5×10^{-3} μm^2. Because most rock samples have low porosity and super-low permeability, hydraulic fracturing stimulation is necessary for commercial production.

2.2. Overview of current brittleness calculation

Typically, rock brittleness can be defined when fractures terminate at or only slightly beyond the yield stress. Hucka and Das (1974) once summarized brittleness indices proposed in different fields using laboratory measured mechanical properties. Vahid and Peter (2003) developed a plastic strain-based brittleness index (B_6) by considering cohesion weakening and friction strengthening based on the mechanism of the brittle failure of rocks. Altindag and Kahramana (2004) defined the brittleness as 50% of the product of the compressive strength and splitting tensile strength of rocks (B_2). Recent studies also reflect that rock behavior information before and after peak strength can provide additional insights into the estimation of brittleness, but the post yield and post failure behaviors of rock are hard to obtain because full cores are sometimes not available (Wang and Gale, 2009). Zhou et al. (2014) put forward new indexes for evaluating brittleness by considering the influences of the yield characteristics and stress states of rock plasticity based on the relative size and absolute value of the stress drop for postpeak strain–stress. Yang et al. (2013) investigated the relationships between brittleness and elastic and strength properties, but unfortunately, no evident correlation was found across all rock types. More authors have tried to explain the general relationship between mechanical-based brittleness and experimental data, but no evidence has been found between brittleness and single elastic parameters. One possible reason is that test results have a high degree of uncertainty when samples are brought to the surface. Mineral content