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RESEARCH PAPER

The nanogranular nature of shale

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Abstract Despite their ubiquitous presence as sealing formations in hydrocarbon bearing reservoirs affecting many fields of exploitation, the source of anisotropy of this earth material is still an enigma that has deceived many decoding attempts from experimental and theoretical sides. Sedimentary rocks, such as shales, are made of highly compacted clay particles of submicrometer size, nanometric porosity and different mineralogy. In this paper, we present, for the first time, results from a new experimental technique that allows one to rationally assess the elasticity content of the highly heterogeneous clay fabric of shales from nano- and microindentation. Based on the statistical analysis of massive nanoindentation tests, we find (1) that the in-situ elasticity content of the clayfabric at a scale of a few hundred to thousands nanometers is almost an order of magnitude smaller than reported clay stiffness values of clay minerals, and (2) that the elasticity and the anisotropy scale linearly with the clay packing density beyond a percolation threshold of roughly 50%. Furthermore, we show that the elasticity content sensed by nano- and microindentation tests is equal to the one that is sensed by (small strain) velocity measurements. From those observations, we conclude that shales are nanogranular composite materials, whose mechanical properties are governed by particle-to-particle contact and by characteristic packing densities, and that the much stiffer mineral properties play a secondary role.

Keywords Shale · Nanoindentation · Packing density · Granular material · Ultra-pulse velocity measurements · Anisotropy · Stiffness

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1 Introduction

Shales are probably one of the most complicated and intriguing natural materials present on earth. The multiphase composition is permanently evolving over various scales of length and time, creating in the course of this process the most heterogeneous class of materials in existence. The heterogeneities manifest themselves from the nanoscale to the macroscopic scale (see multiscale structure in Fig. 1), which all contribute to a pronounced anisotropy and large variety of shale macroscopic behavior. Knowing and predicting the anisotropy plays a critical role in many fields of exploitation, ranging from seismic exploration (log-data interpretation), to well drilling (well bore stability) and production [28]. But so far all attempts have failed to identify the sources of anisotropy, and link mechanical (seismic) properties to composition and structure. The key question that must be addressed is whether there is a link between mineralogy of the clay particles (primarily composed of sandwiched Al–Si sheets) and their in-situ mechanical properties in highly compacted natural materials systems like shales?

In this paper we attempt to provide a first answer to this question. To achieve our goal, we use relatively