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Research paper

Mechanical properties of organic matter in shales mapped at the nanometer scale

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ABSTRACT

The mechanical properties of organic matter strongly affect the way shales deform and fracture. However, the way organic matter responds to mechanical stresses is poorly understood, representing a critical obstacle to assessing oil and gas production in shale formations. Little is known about the mechanical properties of organic matter in fine grained rocks primarily because it often occupies tiny nanometer-scale voids between the mineral grains which cannot be accessed using standard mechanical testing techniques. Here, we use a new atomic force microscopy technique (PeakForce QNM™) to map the mechanical properties of organic and inorganic components at the nanometer scale. We find that the method is able to distinguish between different phases such as pyrite, quartz, clays, and organic matter. Moreover, within the organic component Young's modulus values ranged from 0 to 25 GPa; in 3 different samples – all of which come from thermally mature Type II/III source rocks in the dry gas window – a modal value of 15–16 GPa was measured, with additional peaks measured at ≤10 GPa. In addition, the maps suggest that some porous organic macerals possess a soft core surrounded by a harder outer shell 50–100 nm thick. Thus, our results demonstrate that the method represents a powerful new petrographic tool with which to characterize the mechanical properties of organic-rich sedimentary rocks.

1. Introduction

One of the challenges in developing hydrocarbon reservoirs hosted by mudrock is the accurate prediction of the mechanical properties associated with heterogeneous geological material. Properties, such as the elastic moduli and yield strength, are critical in determining borehole stability and the response of the mudrock to fracturing techniques (van Oort et al., 1994; Mody, 1996; Fam et al., 2003; Dewhurst et al., 2011). Consequently, mechanical properties affect both the efficiency of fracturing methods and the flow of hydrocarbons to the wellbore. In addition, in source rocks containing high levels of total organic carbon (TOC), the elastic properties of organic components affect acoustic velocities and impact seismic expression. However, predicting the mechanical properties of mudrocks is a non-trivial task. Mudrocks often comprise a diverse assemblage of minerals, including clays, quartz, carbonates, and sulfides, as well as varying degrees of cementation and organic matter (OM) content. Further complicating characterization, individual mineral grains are often submicron in size so that mudrocks are in effect complex natural nano-composite materials (Ulm and Abousleiman, 2006), which exhibit a range of anisotropic textures that reflect the shape and orientation of grains.

In mudrocks, uniaxial compressive strength is highly dependent on porosity, varying from around 250 MPa in low porosity (~1%) mudrocks to <10 MPa in high porosity (~35%) dry samples (e.g., Hoshino, 1993; Vernik et al., 1993; Lashkaripour, 2002). In addition to porosity, both small scale intergranular interactions and the mechanical properties – such as the elastic modulus – of the inorganic and organic components can also strongly influence rock characteristics (Benveniste, 1987; Sheng, 1990; Hudson, 1991; Eseme et al., 2007; Scaffaro et al., 2011; Emmanuel and Day-Stirrat, 2012). Although mechanical properties are reasonably well known for many of the minerals commonly present in mudrocks, the properties of organic matter are less well constrained. Further complicating matters, mudrocks typically include a variety of different organic components that undergo considerable changes upon burial: thermal maturation transforms kerogen

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Table 1
Summary of sample characteristics.

Sample	Clay minerals[a] [%]	Silicate minerals[b] [%]	Carbonate, pyrite[c] [%]	TOC[d] [%]	Porosity[e] [%]
Sample 1	16	48	36	4.56	10.9
Sample 2	18	39	43	0.52	4.7
Sample 3	33	49	18	3.01	10.9

[a] Illite, Fe-chlorite (estimated % mass of mineral phases).
[b] Quartz, K-feldspar, albite (estimated % mass of mineral phases).
[c] Calcite, ankerite, siderite, pyrite (estimated % mass of mineral phases).
[d] Total organic content, (% of total mass).
[e] % of bulk volume.

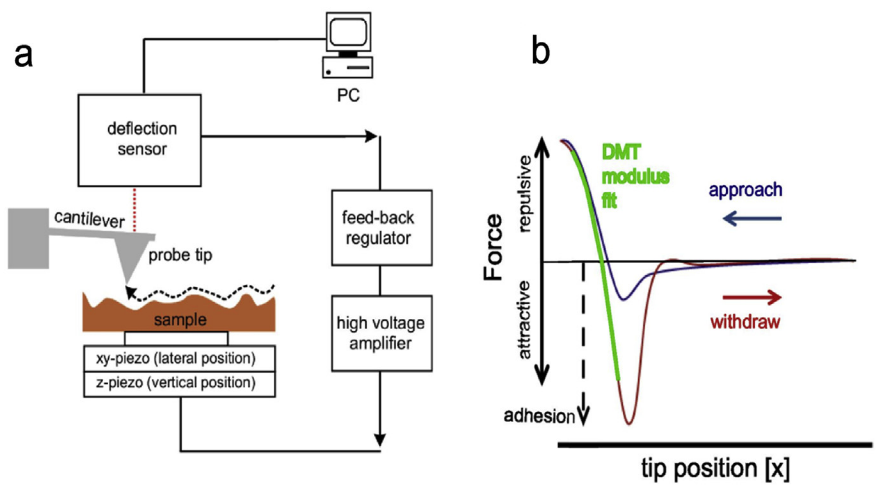

Figure 1. (a) Schematic diagram of an atomic force microscope. (b) Schematic representation of a force distance curve derived using the PeakForce QNM™ imaging mode. Such a curve is derived for each pixel, and parameters including the reduced modulus, surface adhesion, and deformation can be calculated.

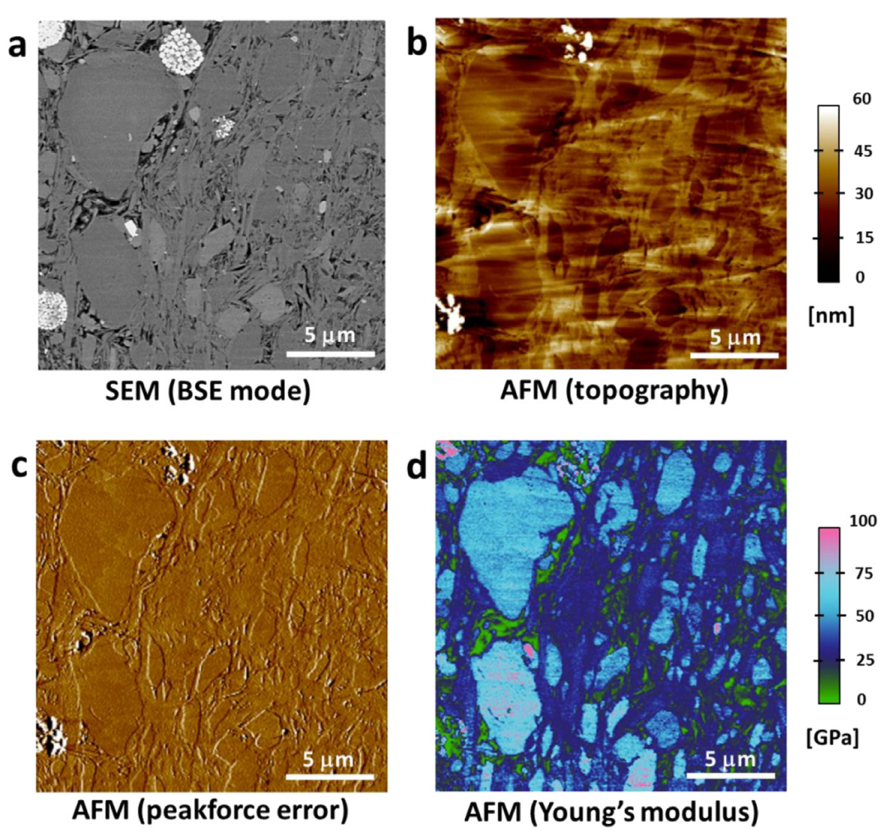

Figure 2. A 20 µm × 20 µm region of Sample 1 scanned using different imaging methods. (a) SEM image (BSE mode); (b) AFM topographic mode; (c) AFM PeakForce error mode used to provide a pseudo-3D image of the surface; (d) Young's modulus map; green indicates organic matter (low stiffness), blue indicates clays, while light-blue and pink indicates quartz and calcite (high stiffness). Modulus values are cut-off at 100 GPa. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)