Commun. Comput. Phys.
doi: 10.4208/cicp.OA-2018-0085

Vol. **28**, No. 1, pp. 518-538
July 2020

Elastic Characteristics of Digital Cores from Longmaxi Shale Using Lattice Spring Models

Ning Liu[1] and Li-Yun Fu[2,*]

[1] *Key Laboratory of Earth and Planetary Physics, Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China.*
[2] *School of Geosciences, China University of Petroleum (East China), Qingdao 266580, Shandong, China.*

Received 31 March 2018; Accepted (in revised version) 31 October 2018

Abstract. Effective medium methods for the attribution of micro-structures to macro elastic properties of shales are important for the prediction of sweet spots in the shale-gas production. With X-ray micro-computed tomography (XMCT), the micro-structures of shale core samples from Longmaxi Formation are visualized and characterized by 3D digital images. As an efficient alternative to conventional effective medium methods for estimating elastic properties, we propose a consistent workflow of lattice spring modeling (LSM) to emulate the digital cores using three types of lattices. Particular attention is paid to investigate the effective Young's moduli, Poisson's ratios, and preferred orientations, by uniaxial compression tests along two directions. Within elastic deformation, the impact of lattice arrangements on the anisotropy is even more than those of stress disturbances and micro-structural features. Compared with analytical approximations and theoretical predictions, the LSM numerical scheme shows general applicability for heterogeneous porous rocks.

AMS subject classifications: 37K60, 65C20, 74B05, 74E10

Key words: Elastic characteristics, lattice spring model (LSM), X-ray micro-computed tomography (XMCT), digital cores.

1 Introduction

Shale gas is a kind of unconventional natural gas that is found trapped within the shale formations. In China, Longmaxi Formation at Sichuan Basin, due to its great deposition thickness, stable distributions and rich organic contents, is currently one of the most important stratigraphic horizons for shale gas exploration and exploitation. Knowledge on

*Corresponding author. *Email addresses:* `lfu@mail.iggcas.ac.cn` (L.-Y. Fu), `nicolaliu@buaa.edu.cn` (N. Liu)

the characteristics of elastic properties, especially those related to TOC (total organic carbon), maturity, reservoir thickness, mineral composition, brittleness, permeability, porosity and pore pressure [1], is imperative for sweet spot prediction. Rather than experimental measurement and theoretical prediction, numerical simulation based on digital cores is an efficient alternative to investigate the dependence of shale elasticity on mineral compositions and micro-structures. Thus, it is fundamental to reconstruct petrophysically the geological structure of shale reservoirs.

For realistic modeling of the shale gas reservoirs, structural characteristics, natural fracture system, multi-fractured horizontal well, and the like, should be taken into account [2]. Currently, the micro-structures can be captured at micrometer resolution by imaging facilities such as scanning electron microscopy (SEM) and X-ray computed micro-tomography (μCT), hopefully enabling the numerical investigation for the relation between micro-structures and the physical or mechanical properties of shales. Based on these high-resolution imaging techniques, howbeit several publications have reported numerical simulations of mechanical and seismic properties of geo-materials mainly implemented by finite difference methods (FDM) and finite element methods (FEM) [1]. Arns et al. [3] used FEM to obtain the elastic properties of Fontainebleau sandstone, which could agree with experimental measurements over a wide range of porosity. With higher resolution representation of complex micro-structural geometries, a deeper understanding of rock properties could be attained, e.g., elastic and transport properties [4, 5], electrical properties [6], pore fluid properties [7] and reservoir characteristics [8]. Zhang et al. attempted to derive the dependence of elastic properties on porosity and kerogen by FEM and described the micro-structural, lithological and petrophysical characteristics of the Longmaxi shale core [1].

Such studies principally are based on the continuum theories, yet it's more suitable to regard the rocks as granular media, which exhibit varying degrees of anisotropy (orientation dependence) caused by their crystalline structure, stress orientations, shape, and configuration. That's because the spatial heterogeneity and material anisotropy strongly influence crack patterns and effective fracture toughness, particularly seismic prospecting [9]. Crampin in his work ever mentioned that the coupling effects among the three body waves (qP, qS_1, and qS_2) motions may be sensitive even to quite weak anisotropy [10]. Therefore, discontinuum based methods which could account for granular texture, particle-scale kinematics and force transmission [11], like molecular dynamics (MD) and discrete element method (DEM), were proposed and developed for granular materials modeling. Hagenmuller [12] acquired DEM models according to the voxel (for 3D)/pixel (for 2D) coordinates, in order to study the rapid and large deformations of granular materials. Even though this kind of grain arrangement is one of the most convenient way to model discontinuum media, it may cause artificial anisotropy [13]. So as to avoid the anisotropic effects linked to regular packings, Harthong et al. [14] generated polydisperse packings to emulate rock masses, using the softer components [15] or discrete fracture networks (DFNs) [16] to represent the local heterogeneity and lamination. To some extent, despite the anisotropic nature of shale could be characterized, the