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Review article

Imaging pores in sedimentary rocks: Foundation of porosity prediction

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ABSTRACT

This review examines the history and current practice of technologies for imaging of pores in sedimentary rocks. Pores are that portion of the rock volume occupied by components of relative mobility such as water of various salinities, microbial life, petroleum liquids, gases, and supercritical fluids. Through a rock's history the contained pores evolve as the primary detrital assemblage responds chemically and mechanically to changing conditions in the subsurface. Description and classification of pores based upon their paragenesis depends upon inspection by imaging that allows the pores to be seen and interpreted in the context of historical processes responsible for formation of the pore walls.

Since the late 1960s, sample preparation and imaging methodologies that clarified our understanding of pores in their correct historical context have been at the root of important advances in prediction of porosity and related bulk properties in the subsurface. These older approaches are now joined by new technologies that serve current efforts to extend predictive capabilities to nm-scale pores in the fine-grained, low-permeability rocks that dominate in the deeper parts of sedimentary basins, and indeed, in the sedimentary record as a whole. Placing the smallest pores into their proper paragenetic context presents a challenge in the quest to develop predictive models for porosity evolution in fine-grained rocks.

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1. Introduction and background

The term "pore" applied in this review (section 1.1) is underlain by the notion that pores are fundamental rock components that, given a suitable imaging method, one might actually *see*.

Modern concepts of pore interpretation and methodologies of pore imaging grew first from studies of coarser sedimentary rocks, sandstones and limestones, and we begin our paper with an examination of this body of work. We review the technological means, both sample preparation and imaging methodologies, that underpin current models for porosity evolution in sedimentary rocks and that serve efforts to extend this understanding to pore systems in the fine-grained sedimentary rocks known as mudstones or shales. In the second half of the paper we consider specifically the current work on pore imaging in muds and mudstones. In some cases, these smallest sedimentary pore systems may be simple analogues of coarser systems, but in other cases, processes in small pores may depart from significantly from those in coarser systems because of the special chemistry and physics that apply at the nanoscale.

1.1. What is a pore?

Pore volume can be considered, most simply, the portion of the total rock volume that is not solid. This viewpoint naturally enables other essential notions: 1. Pores are defined by pore walls. To fully understand the nature of a pore it is essential to discern the character of pore walls; 2. Any particular method of observation (and, indeed, any particular means of bulk measurement) detects only a portion of the total pore population as there are always pores that are blocked from view or too small or too large to be appreciated from a particular image or with a particular method, and, 3. In the Earth's crust pores are never empty—they are not "voids", but host components such as water with dissolved solids, petroleum liquids, gases, a mixture of these or, in the deeper subsurface, a supercritical fluid (Fyfe and Thompson, 1978; Strumm and Morgan, 1996; Tissot and Welte, 1984). Some pores host living organisms (e.g., de la Torre et al., 2003; Kennedy, 1993). Over geologic history pore contents have mobility greater than that of crystalline or other solid rock components (Goff and Williams, 1987; Morad et al., 2000; Parnell, 1994).

The relative mobility of pore contents is responsible for a fourth and quite interesting aspect of pores in sedimentary rocks: the fact that pores change in size, shape, and abundance over time as the rock's solid and mobile volumes respond to shifting chemical and physical conditions in the subsurface. For example, movement of pore contents under sediment loading allows compaction whereas restriction on fluid movement (overpressuring) may retard it. Transport of dissolved components within the mobile rock volume permits dissolution and precipitation of mineral volumes that also yield corresponding changes in the pore volume, both increases and decreases, as pore walls are modified. This paper reviews the various technologies for observing pores in sedimentary rocks and describes some of the outcomes from visual inspection of pores and interpretation of pore histories that have led to models for prediction of subsurface porosity.

1.2. Why look at pores?

Bulk analysis of porosity and pore size distributions in sediments and sedimentary rocks is accomplished by several methods, each with advantages and disadvantages (Doveton, 2014; American Petroleum Institute, 1998; Luffel et al., 1996; Pearson, 1999; Schön, 2015; Tiab and Donaldson, 2015; Van Geet et al., 2000). A key disadvantage to all methods of bulk analysis relates to the limited manner in which such methods contribute to pore classification. Pores can be classified by absolute size (e.g., Luxmoore, 1981; Nelson, 2009; Zdravkov et al., 2007) although a notable challenge concerning the use of size categorization for pores is that an arbitrary name (e.g., "mesopore") applied to a given size range may vary across fields of study or even among different authors in the same field. Pores may also be categorized by relative size (Etris et al., 1988; Lucia, 1995) and by shape (Desbois et al., 2009; Ehrlich et al., 1991). In rocks such categories as size and shape pertain only to the final state of a bulk material that may have undergone substantial change over a history of mechanical and chemical modification (Fabricius, 2007; Katsube and Williamson, 1994). The final size (relative or absolute) and shape of a pore, by themselves, provide only weak clues to the nature and causes of changes responsible for porosity evolution because a given size or shape may arise by multiple pathways of modification.

Although bulk measurements of porosity and knowledge of pore size and shape have tremendous utility for modeling storage and flow behavior, pore categorization that is not referenced to the initial geometry of the rock fabric (solids and pores) is inherently handicapped for assessment of porosity evolution as it lacks information that can be related to timing, mass transport, and volume changes related to mass transport. Prediction of porosity evolution depends heavily on understanding of the local material imports and exports that have affected pore walls of known origins. Pore categorization referenced to the primary detrital framework, a state against which subsequent change can be measured, has a powerful advantage for use in porosity prediction and can only be accomplished by inspection.

Compactional strain (volume loss through mechanical pore collapse) is an important rock modification that can be referenced to the primary depositional framework (Ehrenberg, 1995). Similarly, assessment of mass-balance, the measure of volume losses and gains affecting the mineral fraction, requires an understanding of the primary detrital assemblage as a starting point against which change can be measured (Milliken et al., 1989, 1994). Whether a post-depositional precipitate occupies a primary pore versus a secondary pore (no matter the size) has immense ramifications in terms of the balance of local elemental imports and exports required. Both pore volume and mineral volumes change during rock history and not always in a simple inverse relationship. A mineral (or solid volume) gain does not necessarily result in a pore loss if it is preceded or accompanied by a loss in the mineral volume (secondary pore formation). A mineral (or solid volume) loss does not equate to porosity gain if it is accompanied or followed by compactional collapse or mineral precipitation. Assessing these complex historical exchanges between pore and solid volumes depends upon assessment of paragenesis by imaging.

1.3. Pore categorization based on paragenesis

Primary pores are present at the time of deposition and these can be *intergranular* (between the detrital particles) or *intragranular* (contained within a particle). Primary intergranular pores are the dominant primary pore type within most sandstones and mudrocks (Fig. 1), even after a protracted history of diagenesis (Milliken et al., 2007; Paxton et al., 2002; Scholle and Ulmer-Scholle, 2003). Some carbonate sediments and also some mudrocks contain significant primary intragranular pores (Fig. 2) if complex fragments of bioclastic debris or vesicle-rich pumice are abundant in the grain assemblage (Milliken and Choh, 2011; Milliken et al., 2007; Scholle and Ulmer-Scholle, 2003) (Fig. 1). The primary intragranular pores within biogenic particles represent spaces formerly filled by the living tissue of the organism and