Diagenetic Tipping Points in the Permeability Evolution of Carbonates*

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Abstract

Carbonate rock typing methods aim to associate texture with petrophysically similar rocks. Here, we use 2D thin sections to create 3D pore space models and then extract pore networks to obtain multiphase flow properties using flow models. This novel rocktyping method is applied to an ooid grainstone, of which multiple 3D realisations were obtained. Based on knowledge of the major pore-occluding and porosity-enhancing diagenetic processes, we created a series of synthetic images of the former states of the rock (a process here called 'diagenetic backstripping'). For each stage in the paragenetic sequence, flow properties were calculated. When upscaled to flow units in reservoir models this method then has the potential to identify 'diagenetic tipping' points during the evolution of carbonate reservoirs during burial.

Introduction

Carbonate rock typing methods group petrophysically similar rocks for reservoir modeling, and often attempts to link these to depositional textures. Carbonates, however, often have a strong diagenetic overprint which determines the pore network and multiphase flow properties. Carbonate rock typing based on two-dimensional (2D) petrographic thin section analyses fails to capture the fluid flow properties which can only be achieved with a full knowledge of the multiscale, three-dimensional (3D) network of pores (e.g., Johnson et al., 2010). Diagenesis is often overlooked in rock-typing schemes, and also scaling differences between thin section and core plug often leads to data being poorly constrained around expected trend lines between these two data types.

Recent developments have made it possible to create 3D structures from 2D images and so construct pore architecture models (PAMs) (Wu et al., 2006). These reconstructed PAMs can be used as direct input flow simulations, which allow computation of multi-phase flow properties such as absolute permeability, capillary pressure, and relative permeabilities.

Our approach of creating synthetic 3D reconstructions from 2D images also enables determination of the flow properties of former diagenetic states of the rock. Understanding progressive modification of porosity via an understanding of paragenesis is used here to create a suite of characteristic textures, each representing a former state of the rock that occurred during successive stages of a paragenetic sequence. For each stage in the evolution of the rock, a synthetic 3D structure can be created and flow properties calculated.

The overarching aim of this method is to identify a finite set of representative and successive carbonate rock textures and to associate each with its flow properties in order to establish trends that illustrate the evolution of rock properties for a given starting material (i.e. depositional sediment), and to understand how typical diagenetic processes such as exposure or burial can modify original pore-size distribution to create the final reservoir rock. We seek to create a new 'rock typing' methodology which has the potential to be more rigorous in its selection of rock type boundaries and also allow for nested rock types.

Method

Modelling multiphase fluid properties from 2D images requires obtaining petrophysical thin sections in three orthogonal directions from core (Figure 1).

After conversion to a binary system (0 for solid and 1 for pores), the matrix is then used as a training image to create a 3D Pore Architecture Model (PAM) by stochastic modelling following the method of Wu et al., (2006). The probability of each pixel being in a particular state is determined (or conditioned) by means of a transition matrix of conditional probabilities that is determined from the training (prior) image. This approach uses a third-order Markov mesh and comprises a multiple-voxel interaction scheme (a high-order neighbourhood system) to generate individual realisations that have structure characteristics matching the input data.

From the generated 3D representation of the pore structure a geometrical/topological network is extracted (Jiang et al., 2012; Jiang et al., 2007) consisting of pore bodies (nodes) and pore throats (bonds). This PAM and extracted pore network serves as input for a two-phase flow network model (Ryazanov et al., 2009) to calculate network permeabilities, capillary pressures and relative permeabilities.

By using (stained) thin sections as input, as opposed to greyscale CT-scan data, we can identify stages in the diagenetic history of the carbonate rock and create former states by removing these successive phases, a process we name as ‘diagenetic backstripping’. For each selected former stage in the paragenetic sequence of the rock we create a PAM and use the two-phase flow network model to calculate network permeabilities, capillary pressures and relative permeabilities.

To demonstrate this method was applied to four ooid grainstone samples. 3D structures of 500^3 voxels were created from six 1cm^2 high resolution scans per thin section. The extracted PAMs also contain 500^3 voxels with a voxel size of 20 µm.

Results and Discussion

Two types of cements are observed in the thin sections, a fringing cement around the grains, which was in place before major compaction and a later phase of blocky calcite spar cement. The first is probably related to early marine cementation while the latter is related to late burial.

By artificially removing these cement phases (see Figure 2) we are able to obtain the flow properties of former states of the rock and investigate the evolution of rocktypes. For two PAMs from well A-03, the two types of cements were removed in two steps (2 former states). For two PAMs from one well the syntaxial cements were removed (1 former state).

Figure 3 and Figure 4 illustrate the evolution of permeability, porosity, and relative permeabilities of the carbonate rock during these successive phases of diagenesis. After removal of the cements in all samples it is clear that all had comparable starting porosity and permeability values, i.e. their depositional properties were the same. During burial and subsequent emplacement of cements, the permeability of Samples 1 and 2 had significantly dropped. The formation depth of the different types of cements will be resolved using stable oxygen isotopic signature, which will enable us to tie the observed diagenetic tipping points in permeability evolution to burial depths instead as well as their relative position in the paragenetic sequence.

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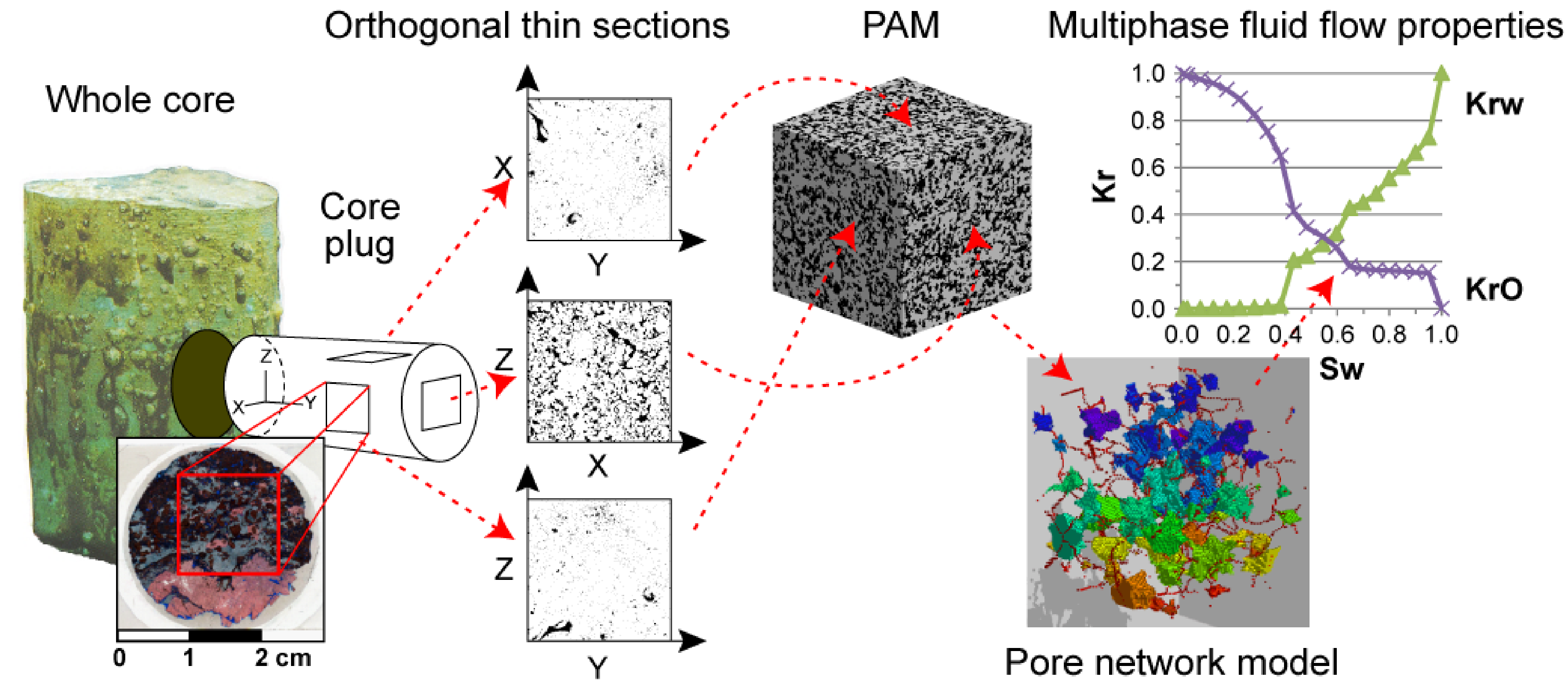

Figure 1. Scheme illustrating the workflow involved to construct a 3D model (PAM) from core plug thin sections and extracted pore network model and subsequent prediction of multiphase fluid flow properties.

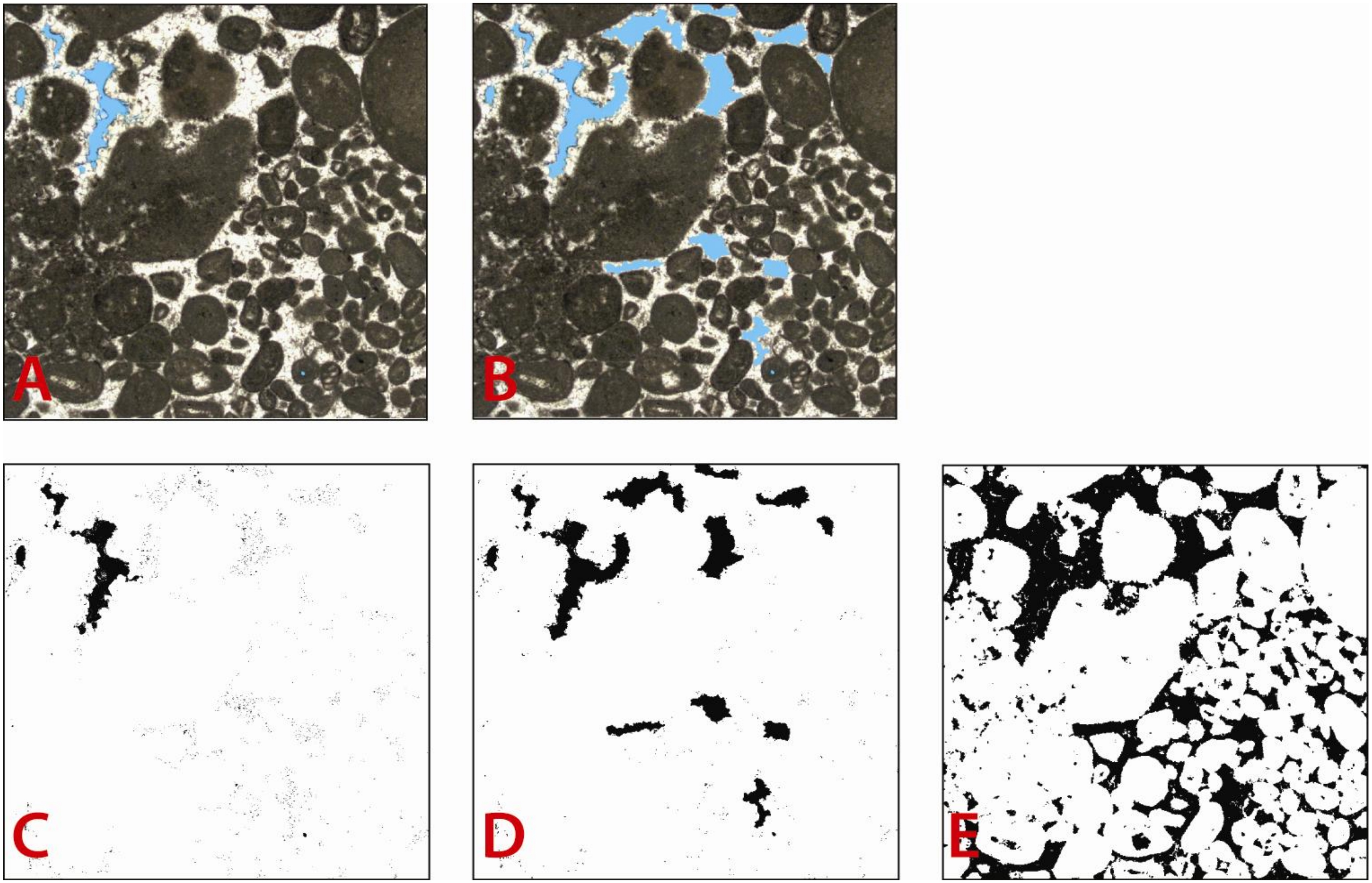

Figure 2. Example of stepwise removal of cements in a thin section. Normal image of the thin section with all cements in place (A) and blocky spars removed and fringing cement remaining (B). After conversion into a binary image (C-E) these images are used as training image to create a 3D structure. Images are 2.2mm wide.

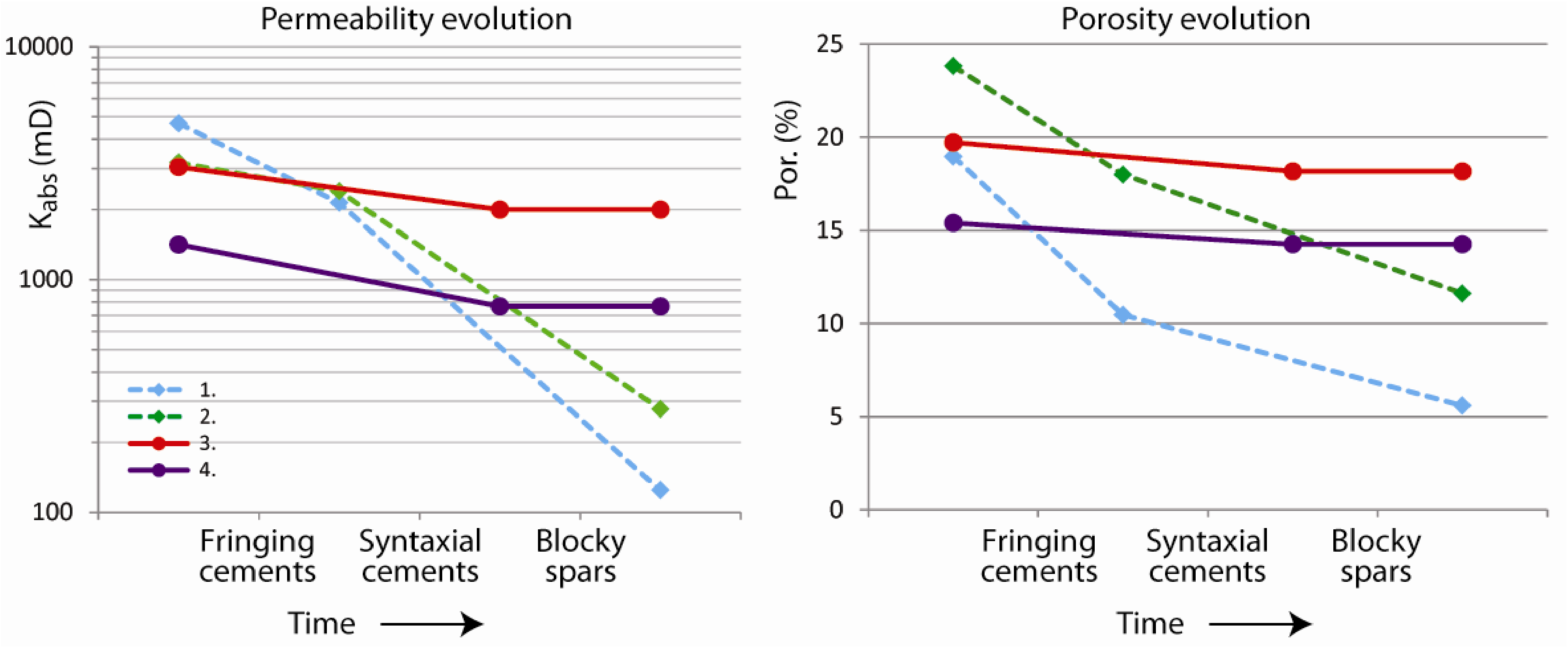

Figure 3. Rocktype evolution through time. Before diagenetic alteration by cementation Samples 1 and 2 were similar to Samples 3 and 4. The labels on the X-axis refer to the types of cements observed in thin sections and their relative timing of formation. The first (leftmost) data point for Samples 3 and 4 reflect rock properties before the formation of any cements, the second data point is after marine cements have formed and the final (rightmost) data point reflects final rock properties with all cements in place.

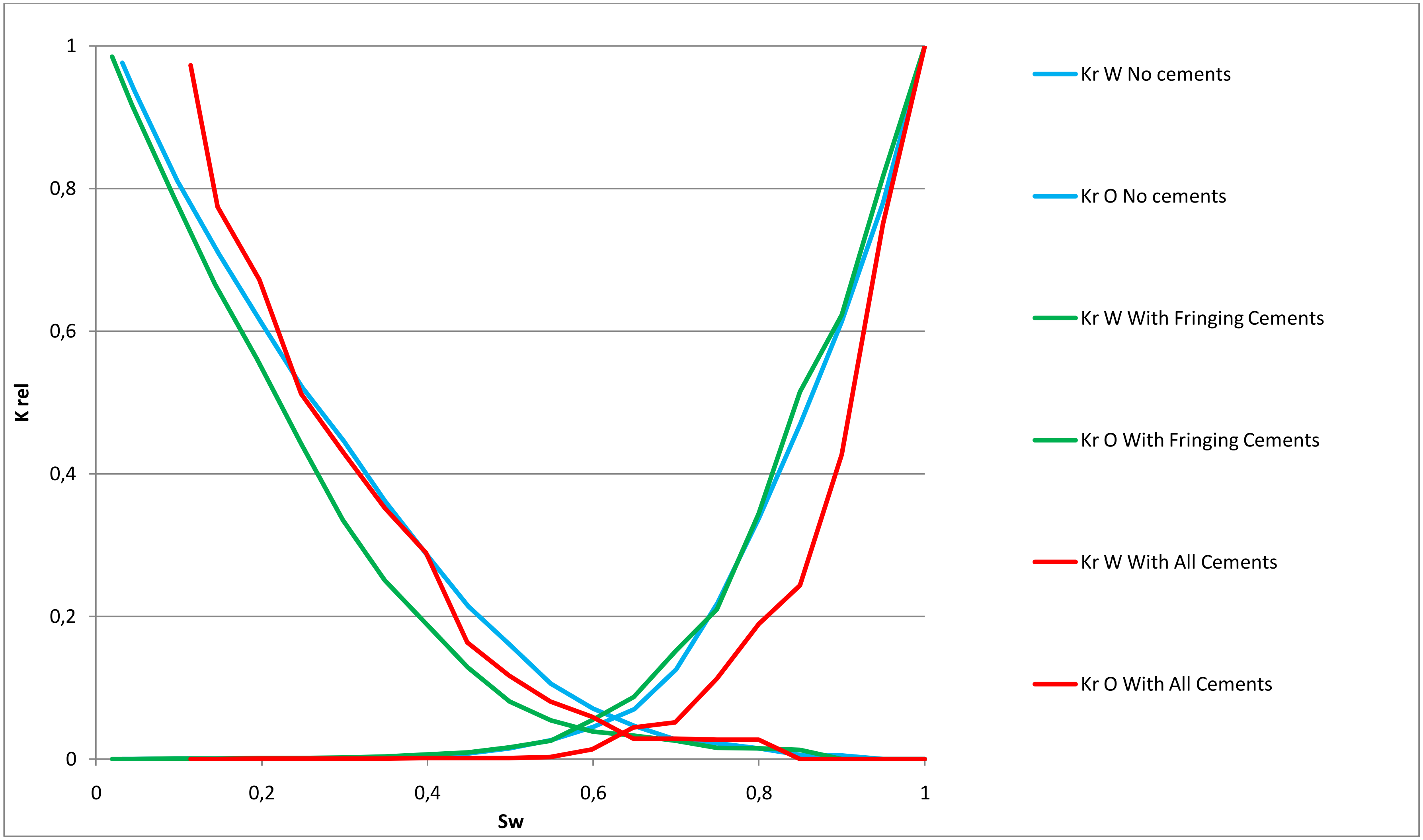

Figure 4. Evolution of relative permeabilities for Sample 2.