Pore network characterization in carbonates based on Computer Tomography (CT) and Nuclear Magnetic Resonance (NMR).

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Aims
Porosity-permeability relationships in complex carbonates are poorly understood. The contribution of micro-, meso- and macropores to the connectivity needs to be unravelled. The aim of the study is to develop a multidisciplinary approach that leads to a better assessment of poro-perm relations. The focus lies on the integrated use of petrophysical analysis, CT, NMR and the necessity of the integration of these techniques for understanding the poro-perm relationships. The samples used for this study are travertines from the Denizli Basin (Ballık area, Turkey) and are selected from four facies: i.e. pool, reed and cascade and waterfall facies (Guo & Riding, 1998).

Method
First, the porosity and permeability are measured on discrete plugs (1 inch diameter), with a helium porosimeter and steady state permeameter. Core analysis was performed by Panterra Geoconsultants (Leiderdorp, The Netherlands). Secondly, pore-size distributions of the samples are determined quantitatively based on CT, NMR and Mercury Intrusion Porosimetry (MIP). A Micromeritics Autopore IV apparatus was used to determine the size distribution for pores with a radius from approximately 3.5 nm to ~ 0.5 mm. It gives thus a quantitative approach for pores of the smallest scale (Roels, 2000). NMR experiments were performed with a Halbach magnet, generating a 0.22 tesla static field in a cylindrical region, with a proton resonance frequency of 9.6 MHz. The total NMR porosity is calculated based on the initial amplitude, since this amplitude shows the response of all water filled pores inside the sample.

A pore size distribution can be obtained with NMR (Coates, Xiao, & Prammer, 1999; Nurmi & Standen, 1997). The NMR relaxivity ($\rho$) is determined, in order to match the calculated MIP pore throat radii distribution with the equivalent NMR pore radii. The equivalent NMR pore radii are acquired by transforming the $T_2$ spectrum with the law of surface relaxivity (Agut et al., 2000):

$$\frac{1}{T_2} = \frac{\rho s}{v} \quad (\text{Eq. 1})$$

Plugs (1 inch Ø) and microplugs (0.3 inch Ø) from the same sample were scanned with a SkyScan 1172 µCT, respectively at voxel resolutions of 28 and 4.8µm³, resulting in the 3D visualization and digitization of the pore network.

Results
Helium porosity varies between 3-45%. Permeability between 0.001 and >10000mD (Fig. 1). In clastic oil reservoirs a linear correlation between porosity and the logarithmic of the
permeability is expected (Nurmi & Standen, 1997). This is however not the case for carbonates especially because of their susceptibility to diagenesis (Anselmetti & Eberli, 1993) and the enormous pore type archive that is encountered in these rocks (Choquette and Pray, 1970). The omnipresent vuggy and reed-mould porosity can help to explain the petrophysical heterogeneity of our samples. Separate vugs and moulds are in particular problematic. These pores are isolated units, or solely connected to the pore network by interparticle or intercrystalline porosity. As a consequence, separate vugs and moulds contribute to the effective porosity, but do not significantly increase permeability, which is mainly controlled by pore throats (Lucia, 2007).

![Klinkenberg Permeability vs Ambient Helium Porosity (1" plugs)](image)

**Figure 1:** porosity versus permeability plot 1 inch plug travertine samples.

The NMR total porosity values are consistently a few percentage points lower when compared to ambient Helium porosity, due to water loss from vuggy pores prior to the measurements. Porosity trends reamin, however, similar. The pool facies averages 5% NMR and 9% Helium porosity, the reed facies respectively 7.8% and 13.5%. The linearity of the porosity trends was verified by calculating the Archimedes porosity. A linear correlation between Archimedes and NMR porosity, with a correlation coefficient of 0.87 was found (Fig. 2). The NMR pore size distribution curve (Fig. 3) matches the MIP curve and for several samples, two distinct peaks were found. The first one contains pores with radii of 1-30µm (micropores), the second one goes from 50-200µm (mesopores).
The variety in pore types is illustrated here by extracting the pore network from CT data of a pool facies plug (Fig. 4A) and a reed facies plug (Fig. 4B). The plug of the pool facies contains irregular pores which align to form alternating bands of highly porous and less porous zones. In the reed facies, however, the porous network is made up of subparallel plant casts. The plants (macrophytes and bryophytes) were in growth position during their
encrustation with travertine. The entrapment of plants in growth position evidences the fast travertine precipitation rates.

**Figure 4:** Plug samples with (a) the pore network of a sample from the pool facies and (b) the pore network of a reed dominated sample. The presence of micropores and mesopores can be demonstrated by scanning a plug and microplug of the same sample. The porosity was calculated for each slice in the microplug and for the corresponding zone of the large plug (Fig. 5). The total porosity increased by as much as 10% for the microplug.

**Figure 5:** µ-CT scans of a cascade facies sample. Scanning both the plug and microplug of this sample reveals the presence of micropores. The frequency histogram of the pore diameters (Fig. 6) reveals a clear shift towards smaller pores for the microplug. The smallest pore objects that could be resolved in the 28µm³ voxel scan have a diameter of ~85 µm. For the microplug the smallest pore diameter decreases to ~12µm (i.e. pores need to have a diameter ≥ voxel resolution *3 to be resolved visually). This
indicates, in accordance with the pore size distribution curve, that pore radii of 1-40µm could not be visually resolved in the 28µm³ scan. NMR and MIP indicate, in agreement with CT, that a significant fraction of the pores and pore throats have radii between 1 and 200 µm and they are present in all four examined facies. These pores are an important part of the pore network and likely play a major role in the connectivity between the separate vugs and moulds.

The extracted pore objects are finally skeletonised (Fig. 7). The colour code relates the width of the pore channels. Dark blue relates to the smallest channel diameter, while yellow and red correspond to the broadest areas. The skeletonised pore network will later be implemented in petrophysical simulations, example permeability measures: effective permeability, apparent-absolute permeability, tortuosity and diffusivity. The simulations will give, together with future tracer and NMR diffusion experiments, a better understanding of the relations between porosity and permeability in these carbonates.
Conclusion

The study illustrates how the combined use of NMR-MIP and CT leads to a better understanding of pore networks in carbonates. Both CT and NMR have the advantage of being non-destructive and they provide crucial information on pore size distributions and the pore network. Facies types have distinctive poro-perm characteristics, mainly depending on vug and mould distribution and their connectivity to the rest of the pore network. Micro- and mesopores could be a controlling factor of the pore network and connectivity in travertine facies. Tracer and NMR diffusion experiments, but also permeability simulations on the skeletonised pore networks, will give a better understanding regarding this topic.

References: