Special Core Analysis Reinvented –

3D Nano-scale Imaging and Computing of Reservoir Rock Properties and Fluid Flow

Digital imaging and computation revolutionised photography by making film cameras obsolete and moving image processing from chemical darkrooms into computers. Ingrain, a Houston-based technology start-up, is using digital imaging and computation to reinvent special core analysis. At Ingrain's digital rock physics lab, latest-generation CT (computed tomography) scanners capture in 3D the actual fabric of reservoir rock samples – the pore-space and mineral matrix geometry fabric – at resolutions as high as 100 nanometres.

BY JOHN B. ELMER

Running on scalable high-performance computing clusters, Ingrain's algorithms simulate various processes in rock, including multiphase fluid flow, electrical current, and elastic stresses. Using imaging and computing instead of physical core analysis experiments allows Ingrain to rapidly measure the resistivity, elastic properties, and absolute and relative permeability, even in ultra-low permeability sandstones and complex carbonates.

Coring is expensive and, in some cases impossible, particularly when new technologies such as coiled tubing drilling are employed. Even if perfect rock material is available, advanced rock property analysis (or SCAL – special core analysis) for relative permeability and capillary pressure is difficult and time-consuming to perform. Houston-based Ingrain has reinvented special core analysis with a series of technical breakthroughs in 3D imaging and computation of rock properties. Physical measurements that require weeks or months in a physical lab can now be completed in a matter of days on any rock material, including sidewall core plugs and drill cuttings.

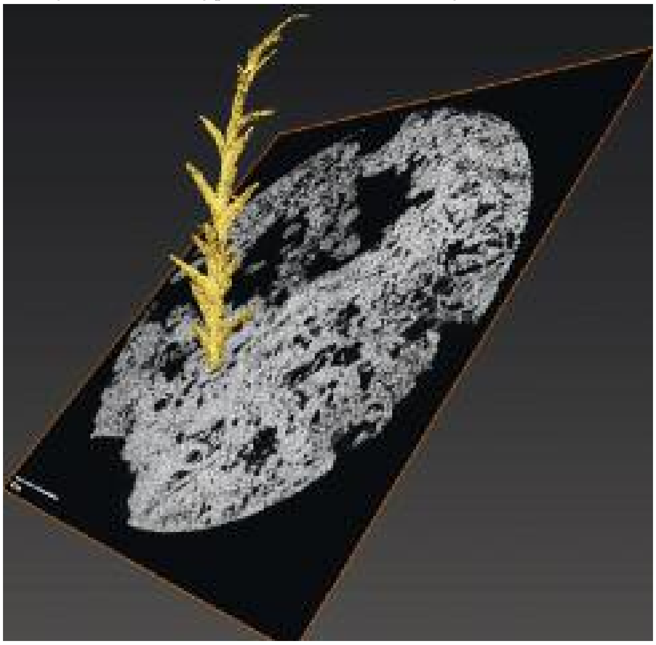
Challenges in Quantifying Carbonate Properties

Extensive databases for the physical properties of sandstones, including those with high clay content, are available from universities and industrial labs. This is not so for carbonates. In sandstones, permeability, resistivity, and elastic-wave velocities correlate well with porosity, grain size, and texture. In carbonates, such relations are very complex and non-unique due to high variability of the pore structure in limestone and dolomite, where large vugs may be adjoined by cracks and microporous patches.

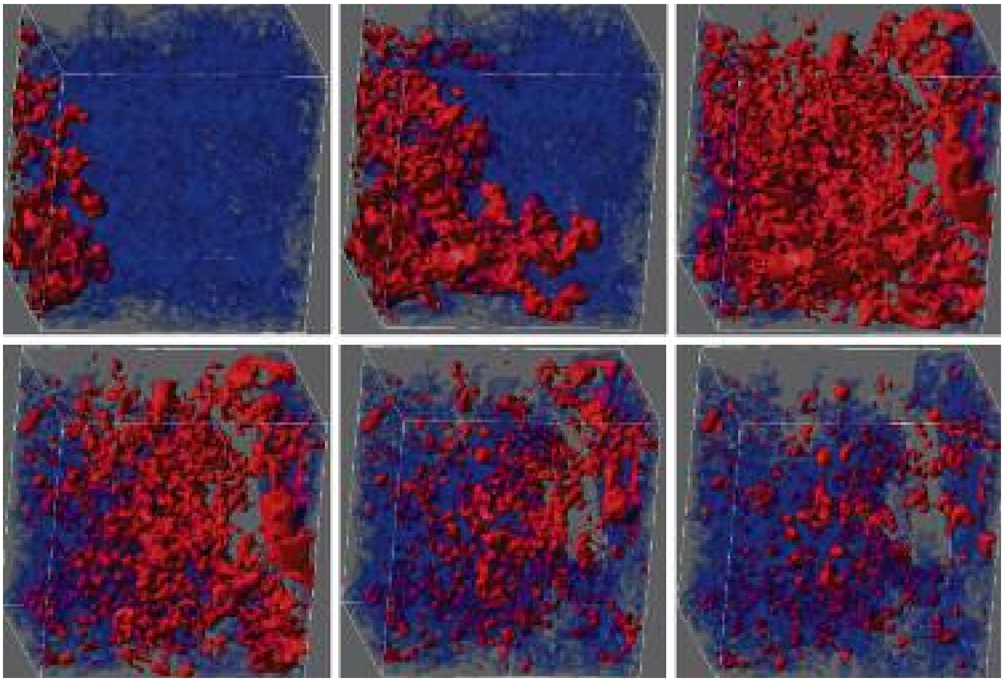
To answer the challenge of capturing predictive relations in carbonates, Ingrain's digital reservoir rock technology makes it possible to quickly analyse rock fragments that represent all kinds of pore structures at multiple scales.

Latest Generation Scanning and High Performance Computing

When analysing core plugs or whole core sections, Ingrain's process begins by having a geologist conduct a low-resolution CT scan to assess the heterogeneity of the rock. The Ingrain geologist uses this scan to decide whether to use a Micro CT scanner (resolution of 1 micron) or Nano CT scanner (resolution of 0.05 microns) to capture the high-resolution 3D image on which rock properties will be computed. The Micro CT scanner requires a 2.5 mm diameter micro-core rock sample, which is taken from a carefully selected location in the core plug or whole core section. If the geologist determines that Nano CT scanning must be used, a 0.5 mm diameter micro-core is taken.
During the 3D scanning process, up to 1,024 separate image captures are acquired from each micro-core or nano-pillar. After imaging, the Ingrain geologist reconstructs the 3D image volume and applies proprietary image processing software to differentiate the pore space from the grains. Within the mineral matrix, Ingrain can reliably identify different mineralogy – pyrite versus calcite versus clay, for example – even when minerals have widely different CT signatures. The final result is a vRock™ digital reservoir rock that



Rendered digital image of a carbonate sample with a fossil highlighted *(illustration: Ingrain)*



Digital two-phase flow: at top, oil (red) migrates into water-saturated (blue) digital sample, and, at bottom, waterflood follows by displacing oil by water ***(illustration: Ingrain)***

preserves the pore space and grain structure in its complete intricacy and makes it ready for computing physical properties and fluid flow characteristics.

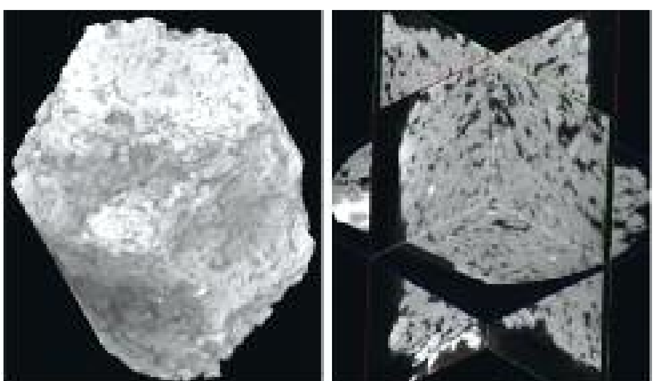
Each vRock™ digital reservoir rock is used to run simulations that precisely mimic controlled physical experiments. Ingrain first computes porosity as the ratio of the number of voxels that fall into the segmented pore space to the total number of voxels in a 3D image. Both effective porosity and isolated porosity are provided.

Absolute Permeability: Ingrain's absolute permeability computation simulates a laboratory measurement within its vRock™ digital reservoir rock. In this simulation, a pressure head or body force is directly applied to a digital sample. The slow viscous flow needed for such permeability estimates is simulated using the lattice Boltzmann method (LBM). The resulting fluid flux is computed and permeability is calculated according to the Darcy's equation. Permeability is computed in three directions in milliDarcies (or nanoDarcies in very tight formations).

Formation Factor: Ingrain computes electrical conductivity (formation factor) in three directions by solving the Laplace equation in the conductive pore space by means of the finite element method (FEM). Ingrain's method directly accounts for conductive components of the mineral matrix, such as pyrite or conductive clay, by assigning appropriate specific conductivity to these components. The electrical current field in the pores is computed and then summed-up to obtain the total current through the sample. The effective conductivity of the sample is simply the ratio of this current to the potential drop per unit length.

Elastic Properties: Elastic properties are computed by simulating a static deformation experiment on the vRock™ digital reservoir rock. The application of stresses to the faces of the sample generates strains in the rock frame that are computed locally using the finite element method (FEM). The resulting effective deformations of the sample are related to the stresses applied at the boundaries to calculate the effective elastic moduli. This application assumes linear elasticity laws are valid within the sample. Therefore, the elastic moduli thus obtained can be converted into the elastic-wave velocities. Results include Bulk modulus (K), compressional velocity (Vp), Young's modulus (E), Shear modulus (G), Shear velocity (Vs), and Poisson's ratio.

Relative Permeability: Ingrain computes relative permeability on the vRock™ digital reservoir rock using the lattice Boltzmann method (LBM). LBM mathematically simulates the equations of multiphase viscous flow by treating the fluid as a set of particles with certain interaction rules between the particles belonging to the same fluid, different fluids, and the fluids and pore walls. Ingrain provides two-phase relative permeability (water-oil, gas-oil, and water-gas displacement at different wettability indices and viscosity values) in three axes, as well as irreducible water saturation and residual oil saturation.



Porosity	9%
Permeability	8 milliDarcy
Compressional-Wave Velocity	6.1 km/s
Shear Wave Velocity	3.4 km/s

A millimetre-size dolomite cutting collected from a deep deviated well – at left, 3D image, and at right, three cross-sections of a 3D image – digital measurements are listed at the bottom ***(illustration: Ingrain)***

Carbonate Rock Properties Analysis Using Drill Cuttings

One application of Ingrain's technology was in quantifying dolomite reservoir properties from drill cuttings that were collected from a deep deviated well. The configuration of the well prevented the operator from extracting core material. By analysing drill cuttings, Ingrain's digital rock physics lab provided the only means for understanding this reservoir and designing production strategy.

A large number of cuttings were processed at Ingrain's Houston lab.

The resulting porosity, permeability, and elastic-wave velocity were consistent with the operator's expectation based on the well's performance. These results also passed Ingrain's internal QC, which employs relevant rock physics models and published data.

Further, the 3D images helped explain the resulting rock properties measurements. The operator was able to identify the most efficient solution for hydrocarbon recovery from the reservoir.

Advantages Over Conventional Physical Lab Analysis

It is clear from the above case that digital rock physics technology has high value in revealing complexity of carbonate and shale reservoirs. But digital rock physics has an added advantage because it produces infinitely reusable digital reservoir rock samples. A digital rock physics database in provides the knowledge to maximise recovery rates in complex formation, where the inherent heterogeneities require large amounts of data to create accurate reservoir models.

Ingrain's digital rock physics lab has several distinct advantages over the conventional physical core lab, for example:

- Providing a detailed 3D image of the pore-space geometry and grain structure.
- Revealing the true heterogeneity of physical properties of each rock sample, enabling more accurate reservoir characterisation.
- Computing a suite of rock physical properties and relative permeability from drill cuttings.
- Delivering fast turnaround in ultra-low permeability formations.
- Preserving the structure of oil sand samples for accurate analysis.
- Conducting repeated experiments on the same sample.
- Safely measuring relative permeability at high temperatures.

Ingrain has made the digital rock physics lab a working reality. It has already significantly complemented and enriched traditional rock analysis done in the lab or well. In the future, digital rock physics can dramatically reduce the need for coring operations, yielding significant savings in time and cost, as well as provide crucial reservoir information in situations where only drill cuttings are available from which to obtain rock properties. ■

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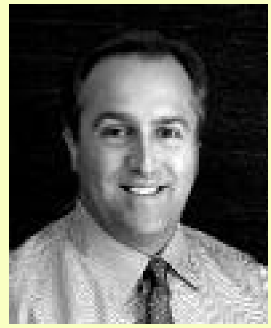

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