Multi-Energy X-Ray Computed Tomography for Source Rock Characterization

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Source rocks are composed of inorganic minerals and organic matter that were compacted during burial and exposed to heat in the subsurface where the organic matter was cracked to light hydrocarbons [1-2]. The inorganic phase of carbonate source rocks is predominantly composed of calcite ($CaCO_3$) but may also contain dolomite ($CaMg(CO_3)_2$), clays (aluminum phyllosilicates), and others such as quartz (SiO_2). The organic matter type also varies and may be kerogen, bitumen, and/or pyrobitumen where the molecular composition diverges with thermal maturity during hydrocarbon generation [2-4]. The texture of these rocks is a result of burial conditions and varies at the submillimeter scale where, in addition to the organic and inorganic components, void space can also exist in the form of pores and fractures. Core analysis techniques are used characterize hydrocarbon reservoirs during exploration prior to field development by measuring rock properties such as porosity, permeability, density, and mineralogy. The measured properties are used to calibrate well logs and to develop empirical equations for log interpretation.

Single Energy X-Ray Computed Tomography (CT) is commonly used to determine porosity and image fluid displacements in conventional sandstones and carbonates where the rocks are composed mainly of a single inorganic phase and relatively large pores. Other CT applications include identifying fractures and determining lithology and mineralogy transitions from whole core as well as local heterogeneity in core plugs. Given that the attenuation coefficient (μ) depends on the X-ray energy and is affected by both the effective atomic number (Z_{eff}) and density (ρ) of the material, distinguishing materials in heterogeneous samples can be challenging as different materials often have very similar μ when imaged with a single x-ray energy. This is especially true for unconventional reservoir rocks with complex compositions and pore-networks. In addition, beam hardening, detector imperfections, and scattered X-rays produce artifacts in the acquired X-ray data. This degrades the quality of the raw data and impacts the reconstructed μ, further reducing the resolution as well as the ability to delineate rock compositions and structure.

Here, we present a Multi-Energy Computed Tomography (MECT) method which is well suited to quantify Z_{eff} and ρ at the millimeter and submillimeter scales. We start with a calibration scan of two known, uniform cylinders, placed side-by-side. We choose their size and composition (Titanium and Teflon® = T&T) to span the range of the materials expected in unconventional source rocks. An industrial CT scanner (North Star Imaging, X5000) is used to collect calibration data at three suitable energies (130, 170, and 210 kVp) for the expected range of Z_{eff}. This data contains the forward map from any pair of T&T lengths to the attenuations at the three energies. To reconstruct from MECT data of an unknown object, the following steps are performed 1) find the pair of T&T lengths that best matches the measured attenuation triplet by solving a non-linear least squares problem, 2) run the Feldkamp, Davis and Kress (FDK) algorithm, and 3) convert the results to Z_{eff} and ρ in SI units using known properties of T&T [5].

Before using the map, each radiograph is deconvolved with a blur kernel that was extracted from the calibration scan. This step suppresses rounding artifacts at rock fractures and other sharp edges. In this pilot study, the source current is set at 50% of detector saturation to avoid gain non-linearities. The data is collected at 16 frames per view for 1440 views, which is slow, but keeps the detector lag and counting noise low. The calibration object is similar to the source rock core plugs, hence the scattered X-ray signal is partially accounted for by our inversion map.

For denser and larger objects, scattering becomes a greater source of error, which can be corrected for with a Beam-Stop Array (BSA) methodology [6].

The method was first tested using homogeneous standards of known Z_{eff} and ρ including the basis materials. The results show that the MECT-measured Z_{eff} and ρ for individual and groups of standards are close to the true values. Next, the method was applied to source rock core plugs which are heterogeneous composites comprised of inorganic and organic components as well as void space in the form of pores and fractures. The average Z_{eff} and ρ determined by MECT were consistent with independent measurements of ρ and Z_{eff} based on the composition of these samples. In addition, MECT was used to identify Z_{eff} and ρ at the submillimeter scale and assign regions of similar values to specific mineral and organic phases. By applying the MECT method to source rock plugs, the variations in the inorganic and organic components of the plug was measured directly from CT reconstructions. Finally, the average Z_{eff} and ρ for each slice were used to generate a high-resolution digital log to identify micro-scale variations in mineralogy and organics content.

Ultimately, the MECT method expands the operational envelope and value of CT imaging for quantitative core and core plug characterization.

References

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[7] Acknowledgement. A. Katsevich is a shareholder and chief technology officer of iTomography Corporation and, as such, may benefit financially as a result of the outcomes of the work reported in this publication.