CORE IMAGING – TWENTY FIVE YEARS OF EQUIPMENT, TECHNIQUES, AND APPLICATIONS OF X-RAY COMPUTED TOMOGRAPHY (CT) FOR CORE ANALYSIS

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ABSTRACT

Over the past twenty-five years, X-ray CT technology has shaped and advanced core analysis with a momentum similar to that of the growth of the Society of Core Analysts (SCA) itself. From the initial work in early 1984 to the present day, we have seen a dedication of efforts from individuals, and the development of technology that has significantly advanced our understanding of porous media.

In this paper we will track equipment development and techniques that have been successfully applied and modified for the special case of imaging porous media. The early developments in the technology provide a basis and common understanding necessary for subsequent higher-level techniques and applications. The primary focus of this paper is to show how the technology has been applied to both static and dynamic reservoir models, using examples from both the US and the Middle East. We look at how the costs of equipment, data acquisition time, and data size have all influenced how and when the technology was applied economically. We discuss how the information from this visual and quantitative tool can best be handled to integrate its value throughout the workflow from geological description to production enhancement. On another scale, notably of emerging significance, we discuss the "younger" X-ray CT sibling, micro-CT. The rate that this technique is maturing is due in no small part to the lessons learned from the "older" CT technology. Forward looking, we venture forth with our ideas and projections of future applications and developments.

INTRODUCTION

At the First Annual Technical Conference of the SCA in 1987, 7% of the presented papers referenced X-ray CT scanning. However, at the International Symposium of the SCA in 2010 that number had risen to over 25%. As indicated, CT scanning climbed a rapid technological curve throughout the 1980's. Figure 1 shows the remarkable growth in publications that included the keywords "X-ray CT" and "core analysis". The spike in the year 2003 represents the group of papers that first appeared in the often cited Geological Society Special Publication 215 (Mees *et al.*, Eds., 2003).

By the end of the 1980's, with CT scanning of cores becoming essentially a commodity, future improvements in techniques became tailored to more specific applications. These include, to mention a few, the quantitative analysis of determining bulk density by CT scanning (Kantzas *et al.,* 1992), gas-water relative permeability measurements of carbonate cores under different wetting conditions (MacAllister *et al.,* 1992), in-situ saturation monitoring of enhanced oil recovery (EOR) floods (Alvestad *et al*., 1992), and the study of hydrate dissociation in a hydrate/sand mixture (Tomutsa *et al.,* 2002). An early CT methodology was demonstrated for mapping the patterns of natural fractures in full-diameter core (Bergosh *et al.,* 1985). The petroleum industry's need for improved process understanding and advanced mathematical modeling has more recently transitioned CT's resolution requirements from the macro scale to the micro scale (Coles *et al.,* 1994).

X-RAY CT EQUIPMENT

Although computerized tomography for medical applications can be traced back to the late 1960's, one of the first uses for displacement in porous media occurred decades later (Wang et al., 1984). Similar applications for non-medical use were available in Austin in 1983 (Scientific Measurement Systems). Initially, scanning was used for inspection of ancient artifacts and industrial work (Lampe, 1983). This early equipment was a very large machine with a radioactive isotope source (^{192}Ir or ^{60}Co), heavy rotating stage, and a computer system (PDP-11/24) located outside of a leaded and brick-walled environment. An experimental core flood performed on the equipment in mid-1984 and is shown in Figure 2(A). The equipment was also used to investigate the potential use of serpentine cores to eliminate end effects as shown in Figure 2(B).

During the 1980's a significant step was also taken with the more practical transition of adapting the CT scanner from the hospital to the oil industry laboratory (Hurst, 1984). The Hurst article describes the pioneering developments of Shell scientists Vinegar and Wellington, who modified a medical CT scanner (Technicare DeltaScan 100) for core analysis use (Figure 3A), paving the way for decades of use (Figure 3B).

As the technology has advanced throughout the past twenty-five years, the model year difference between those used in the petroleum labs and those used in hospitals has decreased. CT applications for special core analysis were rapidly realized that included porosity and relative permeability determinations, and the three-dimensional display of fluid movement within cores and well-pattern models (Withjack, 1988; Withjack and Akervoll, 1988). For most of these later investigations, newer CT scanners were in use that utilized a bank of fixed detectors and a rotating source (Fourth Generation scanner, Figure 3C). These upgraded scanners provided greater power, higher resolution, and decreased scan times from 20 seconds to typically 1 to 2 seconds. Current multi-slice CT systems like those shown in Figure 3D are capable of continuous scanning (0.5 mm slices) of a three foot core in helical mode in a matter of minutes.

Currently, the use of an X-ray source with a dual focus spot (5-10 micrometers), coupled with an image intensifier and a CCD camera, forms the basis of micro CT scanners (Figure 4). Table 1 summarizes characteristics of the CT scanners used by the industry over the past several decades. This brief list only samples some of the systems and the extensive research contributed to CT technology over the years (Akin and Kovscek, 2001; Withjack *et al.,* 2003).

As hardware improved, the BASIC operating systems gave way to UNIX, and now to a more common Windows system. Improvements in image files required improved data storage and transfer. When working with adapted medical systems, the presence of medical patient information protection still perplexes the petroleum scientists.

CT TECHNIQUES

Calibration / Tune-up / Artifact Reduction

The CT determined linear attenuation coefficients are correlated to the bulk density of the material. However, as early researchers quickly observed, the calibration or "tune-up" used by medical radiologists was not the optimal one for scanning dense rocks. For a consistent mineralogy, a near linear calibration was available as shown by Vinegar and Wellington (1987). In samples with variable mineralogy, additional calibration lines are needed. Commonly, porosity is determined as the ratio of CTN differences (CT numbers in Hounsfield units) with the fluid-filled and dry core difference divided by the fluid and air difference, as shown by Withjack (1988) for brine saturated materal and Moss (1991) for xenon gas filled pore space.

$$\phi = \frac{CTN_m^f - CTN_m^{vac}}{CTN_f - CTN_{air}} \quad \text{...(1)}$$

These measurements take full advantage of what the radiologists refer to as contrast agents. The addition of sodium iodide (NaI) to brine or iodododecane to oil greatly increases the X-ray adsorption, expanding the dynamic range of equation (1). Xenon gas fills a similar role and is a useful tool, especially in tight formations. A third approach advocated by several authors (Wellington and Vinegar, 1987; Siddiqui and Khamees, 2004) uses dual energy measurements to obtain true bulk density and effective atomic number (Z_{eff}) simultaneously.

Acquisition and Display

The qualitative visual information provided by the CT is often as important as the quantitative linear attenuations. Traditionally with medical systems the acquisition and display processes are two-fold. An initial "delta-view" or "scout" image is determined with the CT scanner operating to provide digital radiographs. The position for axial slices is determined and the second step of acquiring radial slices is initiated. A typical image for sections of sandstone and carbonate are shown in Figure 5. The positioning system on the early scanners and even some of the current systems impacts core processing and preservation at the well site. Sections longer than one meter typically cannot be scanned in a single pass (earlier systems had an even shorter range). Hence core tubes longer than one meter are generally discouraged for large cored intervals. Although generally used as a quantitative tool, proper calibration can provide a rapid determination of net pay in complex sand shale sequences and degree of fracturing for completion targets. In an innovative technique and one that was slightly less expensive, a combination of digital radiography and two dimensional movements were used in a similar way to provide visual CT image videos during the early 1990s (Core Labs X-ray videos). The 3D interpretation by the viewer still highlights the ability of the human brain to outpace even our best GPU image processors.

The second step in the display of the data is the visual presentation of the axial slices. These 2D data can be at discrete spacing or in a continuous mode. These stacked images provide the best use of the technology whether for static core characterization or for dynamic fluid transport. Key to the increased use of the technology, as seen in the post 1990 years of the reference plot, is the improved speed of image acquisition. The medical driver for cardiac imaging has provided the technique of helical scanning that has been rapidly applied to fluid transport imaging. Early Deltascan 100 image sequences that took hours can now be done in seconds using sixty-four (64) detector banks and helical scanning. A revitalized use of the continuous scans relies on imaging the exterior surface of the core for comparison with the formation micro-imager (FMI) logs (Siddiqui *et al.*, 2003). The un-rolled CT image can be oriented by direct correlation with oriented image log. The result is an oriented core set for anisotropy determinations. An example is shown in Figure 6.

CT Image Analysis

Processing of CT images initially used simple rendering and often only thermal image plots of the results. Early in-house UNIX-based software gradually gave way to the more complete commercial systems used today. Early set-ups included multiple platforms and multiple hard-copy output devices. In a typical set-up today the multiple platforms have been replaced by multiple workstations and a server for data storage. Readily available commercial software can now bring in Gigabyte image stacks and provide 3D analysis and multi-platform graphical output. In some cases the CT image processing workstations now resemble special effects studios more than do research laboratories.

STATIC MODEL APPLICATIONS – FORMATION EVALUATION

The description of a reservoir static model relies on characterization of the productive units over a range of scales from micro-to-macro. CT technology has evolved, perhaps in a reverse order, from macro-to-micro, with the growth of new developments and capabilities realized by researchers in the field. Earliest to benefit from CT was the analysis of whole core to provide integration with logs and qualitative use to characterize fractures. Later developments included smaller scale work to test the viability of using CT quantifications for mineralogical analysis, and work to improve understanding of rock heterogeneity and permeability.

Porosity and Porosity Variation - Capitalizing on Partial Volume Effect Errors

In medical parlance the characteristic of primary interest of petrophysicists *(i.e.*, porosity) is fundamentally considered to be an artifact due to a partial volume effect. Although the rock sample fills the scan slice, each voxel is a mix of both solid and void space. The result is a two dimensional CTN variation that can be equated to porosity, and with some additional calculations or correlations, pore volume and permability. Moss and Russo (1991) showed how the portion of the secondary porosity identified by the CT could be equated with permeability.

Core-Log Integration

X-ray CT scanning of whole cores provides visual presentations of core quality, homogeneity, and density variation. It also provides a complete set of closely-sampled direct log-correlated measurements. From the left track to the right track of a typical log presentation there is an equivalent or comparable measurement derived from X-ray CT. Core gamma–ray runs used for depth adjustment and log gamma-ray intervals used for the identification of sand-shale sequences are easily augmented or replaced with bulk density values and CTN variations that are matched with downhole porosity runs. In some cases the data provided by initial scout images, as shown in Figure 5, are sufficient. In others, simple three point averages can be used to depth match not only 30 to 90 ft intervals but also groups of meter length tubes that may have been misplaced at the well site. Figure 7 shows a match of CTN with a bulk density log.

Dual-energy scans provide a complementary tool for most lithology computed tracks through the calculation of an effective atomic number plot. Combined with CT derived porosity and transformed permeability these can be used to identify and characterize specific electro–facies or petrophysical rock types. Figure 8 shows an example for a typical mixed carbonate core. When used as a simple SCAL saturation tool, either in preserved and re-saturated whole cores or for plugs instrumented for resistity, the relative uncertainty of both formation factor and resistivity index measurements is reduced. As an orientation and fracture characterization tool X-ray CT scanning often provides one of the most cost-effective technologies for selective perforations. Unrolled images from continous CT scans can be used to orient the direction of a core. Individual slices can be used to quantify fracture direction and intensity with direct impact on the selection of preferred completion intervals and perforation directions.

DYNAMIC MODEL APPLICATIONS – RESERVOIR ENGINEERING

An area that has benefited greatly from CT applications is the modeling of fluid flow within porous media. A major key to asset evaluation is reliable performance prediction, which typically relies upon numerical simulation performed by the reservoir engineering team. With the ability to monitor fluid movement within corefloods, the CT scanner can provide qualitative understanding through visualization, and the quantitative data to validate the performance of a simulator for a displacement process. With such validations realized, the simulation can be carried-out at the field scale to provide optimizations for field exploitation.

Visualization and Quantification

Early investigators used CT for observing the distribution of oil and water saturations during corefloods (Wang *et al.*, 1984), and revealing the influence of sedimentary features (Honarpour *et al.*, 1985). A comprehensive study on the methodology and application of CT scanning for coreflood monitoring became available (Wellington and Vinegar, 1987), including a recommended protocol for determining the saturations of three fluid phases using dopants and dual-energy scanning. These authors further demonstrated CT observation of miscible core floods, and the coupling of CT monitoring with simulations (Vinegar and Wellington, 1986; Wellington and Vinegar, 1987).

CT imaging techniques make it possible to visualize and quantify many core phenomena during miscible and immiscible displacement experiments that are otherwise undetectable by standard practices. For example flood front tracking (Wellington and Vinegar, 1987), visualization of saturation distributions (Withjack, 1988; Siddiqui *et al*., 2000; Al- Enezi *et al.*, 2008), and mud invasion (Auzerais *et al.*, 1991). Examples from a medical CT system are shown in Figure 9, and detailed images from a micro-CT investigation of fracture flow are shown in Figure 10.

PRODUCTION ENHANCEMENT

In reservoir rock, acid treatments are typically used for scale removal, but may also result in deep damage through the precipitation of acid-treatment byproducts. The application of CT for acid treatment design was recognized early by Bartko *et al. (1995)* and resulted in optimization of an acid treatment for a sandstone sample from an Alaskan field. Bazin *et al*. (1996) utilized CT to visualize the limestone dissolution and acid wormhole growth; their work confirmed the industry accepted relationship between applied pressure differential and wormhole length. Further studies investigated the advantages of using both conventional and emulsified acid treatments in carbonate formations. At low rates, acid-in-diesel emulsions provided deeper penetration, while at high flow rates, plain acid yielded lower penetration but more effective stimulation (Siddiqui *et al.*, 2006). Figure 11 shows the extensive development of production flow path with the use of emulsified acid.

Krilov *et al.* (1996) presented a CT methodology for hydraulically induced fracture identification and azimuth determination. Investigation of perforator effectiveness has been studied using conventional X-ray analysis (radiographs) for several decades. In an early paper, Aseltine (1985) showed that perforation mechanics in rock are very complex, and expressed a critical need for test data to advance design. Today, with the availability of CT, data can be obtained to measure both the axial and radial growth of a perforation, as well as track its path (Figure 12**).** Karacan and Halleck (2002) recently reported on the application of CT for perforator analysis with underbalanced conditions. Their paper reports very different results for gas and liquid saturated cores, with less perforation damage in liquid-saturated cores. In a study of perforations in tight, naturally fractured reservoir rock, Halleck and Dogulu (1996) used CT to investigate jet penetrations across fractures. They reported that stresses from shaped charges caused deformations that sealed fractures where they intersected perforations.

UNCONVENTIONAL SOURCES

In addition to the improved rock chacterization provided by X-ray for unconventional sources, the visualization capabilities can be used to illucidate and quantify the unconventional displacements associated with these sources. A CT study of hydrate dissociation was reported by Tomutsa *et al.* (2002), which confirmed the CT method to track the progression of a dissociation front in a hydrate/sand mixture. Early work with xenon gas and a fourth generation CT scanner by Moss *et al.* (1991) showed the dual porosity controlled flow rate dependence for samples of Montery and Bakken shales and coal.

PORE SCALE CT IMAGING - THIN SECTIONS IN 3D

The rapid use and adaptation of non-destructive medical X-ray CT in several petroleum fields opened the doors for additional techniques. One that quickly followed was the use of finely focused X-rays. Initial work using an X-ray focal spot size of 1 to 5 microns (Jasti *et al*., 1993) or mono-chromatic diffracted synchrotron radiation (Coles *et al,* 1994) provided three dimensional petrographic images that opened a wealth of possibilities. The corresponding rapid rise in computation engines provided the impetus to mesh computational fluid dynamics (CFD) with the now visible complex pore space. The well used pore cast image of Wardlaw (1980) could now be obtained non-destructively and manipulated digitally.

Comparisons of medical and micro CT systems are shown in Table 2 (Sarker and Siddiqui, 2009). Images for an assortment of reservoir rocks from recent carbonate sediments to Permian aged sandstones are shown in Figure 13A-C, which were taken with a micro-focused X-ray tube and flat panel detector. They compare favorably with Figure 13D which was taken using a synchrotron source. As the group of other papers in this Conference shows, the technique and corresponding calculations are one of keen interest to the SCA.

DISCUSSION

All of the fundamental engineering parameters associated with hydrocarbon recovery-storage capacity, productivity, and recovery can be inferred either directly or through a combination of X-ray attenuation measurements. This physical principle is one of the main reasons CT scanning has seen such a rapid development and deployment in the petroleum industry. The 3D capabilities introduced with the adaptation of medical instruments converted our initial 1D and 2D extrapolations into simple interpolations. The three dimensional image provided a more realistic view of our natural 3D reservoirs. CT scanning provided petrophysicists with real time 4D measurement capabilities well before geophysicists coined the term. Our ability to visualize transport mechanisms, fronts, and breakthroughs fills a gap where intuition fails. For the production engineer, CT scanning provides a qualitative and quantitative technique to design and test formulations and methods.

As a non-destructive technique, micro-CT scanners benefited from the early medical work that sought smaller and a denser packing of detectors. The advances in computing and digital data transmission shortened the development and adaptation time and the extension to even finer scales with nanometer CT resolution. With petrophysical medical CT experience and fine scale image capabilities future applications that elucidate fundamental interactions and unconventional resources can be expected. In summary:

1. The CT scanners have provided advances in the study of reservoir rock cores and flow through porous media.
2. The cost of utilizing CT for core analysis is small in comparison to overall project value (NPV), and can improve the value of a well.
3. Micro-CT is a viable technology that can provide new data for improved pore-level modeling and mechanistic understanding.

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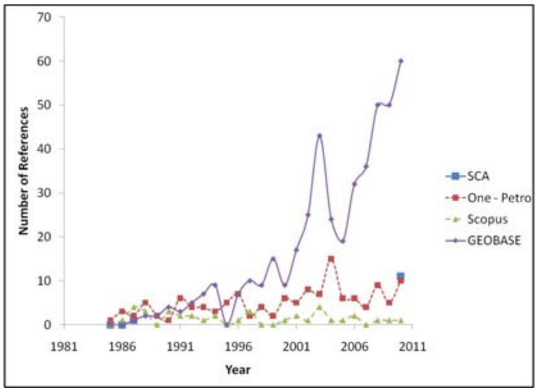

Figure 1. X-ray CT and core analysis articles 1985-2010.

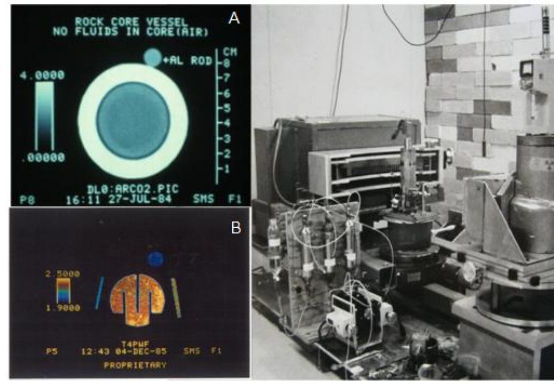

Figure 2. Early material inspection gamma-scan system used for core flow visualization (A) (Withjack, 1984) core flood (B) serpentine flow study.

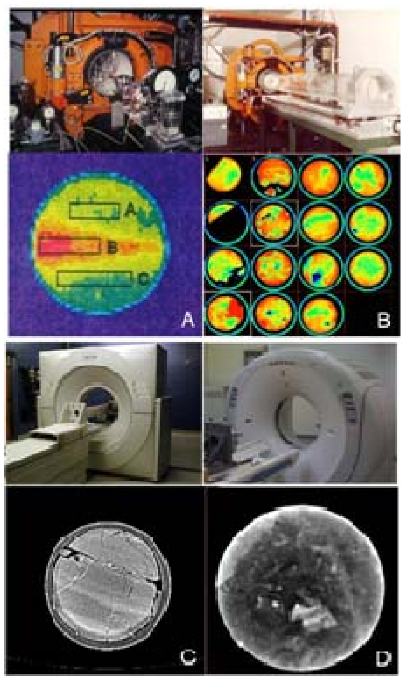

Figure 3. CT Generation machines. 2nd Generation Delta-Scan 100 (A) Core flooding 1984 (B) Reservoir characterization 2000 (C) Fourth Generation Picker axial slice (D) Single slice form Helical Scan Acquilon.

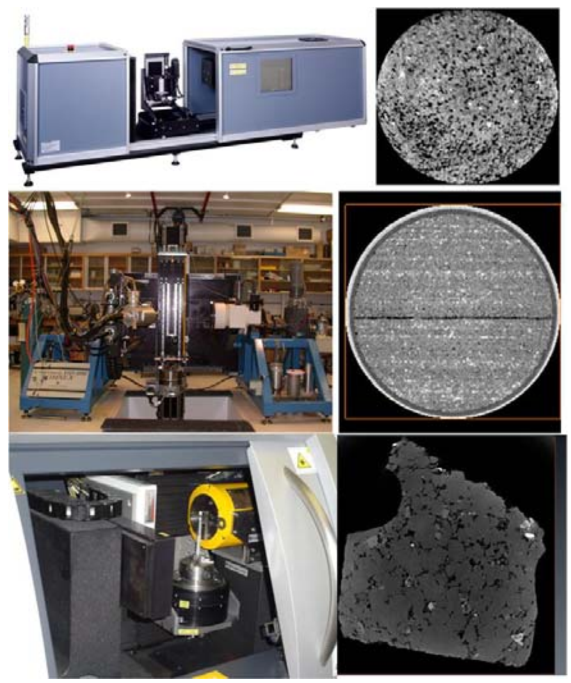

Figure 4. Micro-CT Systems.

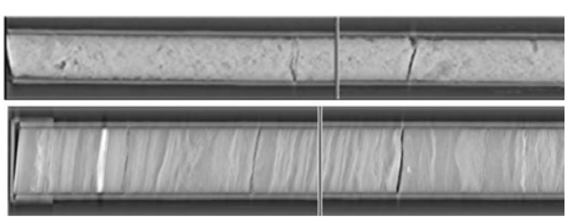

Figure 5. Pilot or Scout images for 2 5/8 in. carbonate core and 4 in. sandstone core.

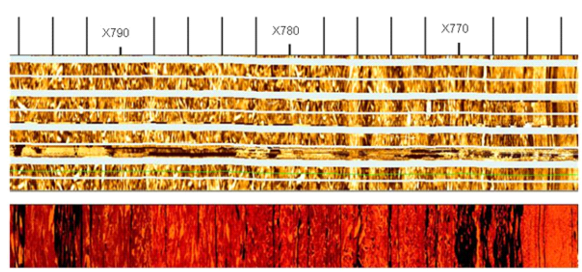

Figure 6. FMI (top slices) and unrolled CT image for carbonate core.

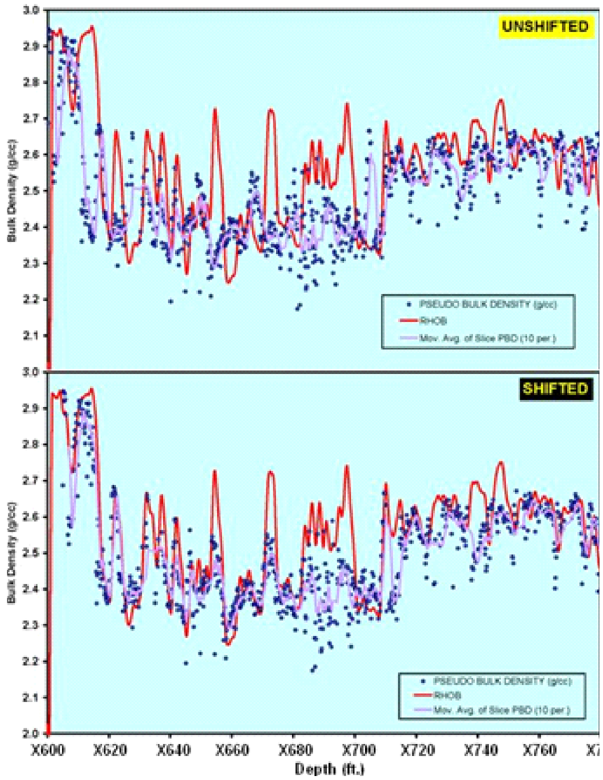

Figure 7. Carbonate Core depth shift using bulk density log and pseudo-bulk density (PBD).

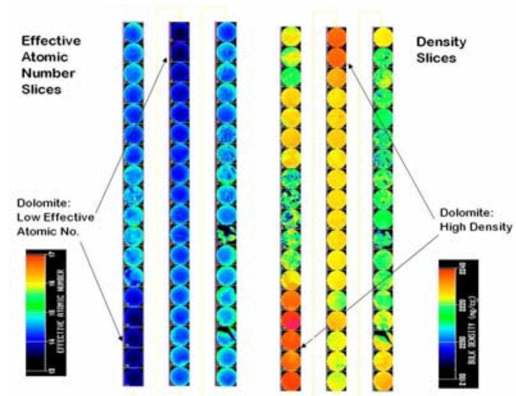

Figure 8. Computed results from dual Energy CT scans 140 kVp and 80 kVp.

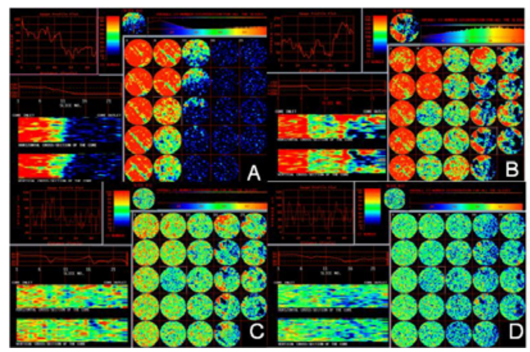

Figure 9. Two-phase displacement in composite core. After partial oil injection (A) at Swir (B) after 1 PV waterflood (C) after 20 PV waterflood (D).

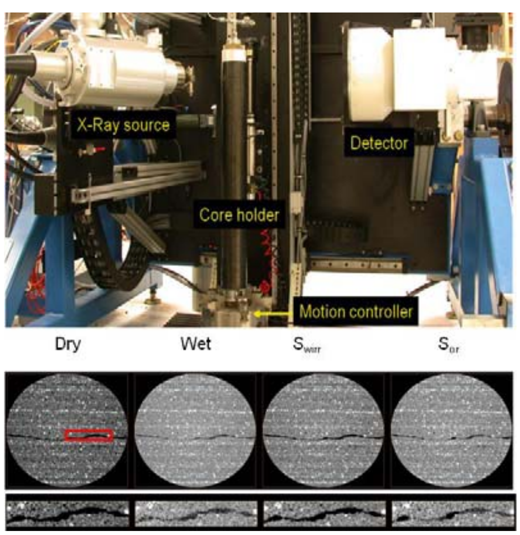

Figure 10. Two-phase fracture flow in micro-CT system.

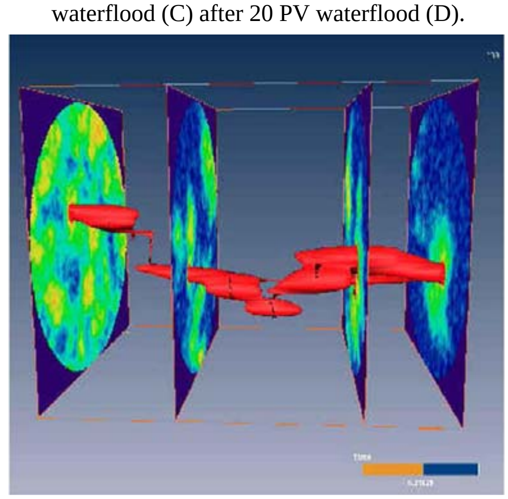

Figure 11. CT observed wormhole development due to acid.

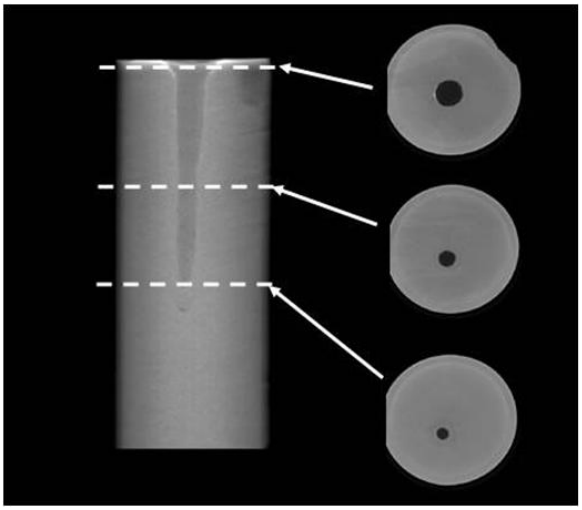

Figure 12. CT inspection of perforation shot penetration.

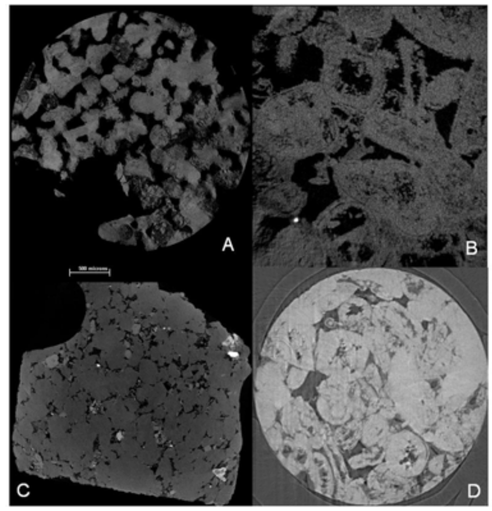

Figure 13. Micro-CT images. Recent sediment (A) Jurassic carbonate (B) Permian sandstone (C) Synchrotron image, Jurassic carbonate (D).

Table 1. Examples of Petroleum Industry X-ray CT scanners

CT Scanner	Generation	Operation		Images		Years in Operation
		kVp	Max mA	Display	File Type	
DeltaScan 100	Second	120	25	256X256	Generic	1984-2004
EMI 5005	Second			256X256	Generic	
ELSCINT	Second				Generic	
Technicare 2020 or 2060	Fourth	140	100	512X512	Generic, DICOM	1985-2010
GE 9800	Third	140	600	512X512	Generic, DICOM	
Picker PQS	Fourth	140	200	512X512	Generic, DICOM	1998-2010
Toshiba Aquilion	Third	135	125	512X512	DICOM	2009 - Present

Table 2. Medical CT and Micro-CT Operating parameters

	Medical X-ray CT	Microfocus X-ray CT
Geometry	3rd Generation (fixed object, rotating source and rotating detectors) some 4th Generation (fixed object, rotating source and fixed detectors)	Modified 3rd generation (rotating object, fixed source and fixed detectors)
Volume Imaging	Object movement orthogonal to the scanning plane	Object rotation
Beam	Fan beam	Mostly cone beam
X-ray Source	High Power (80-140 kVp, 50-400mA)	Low Power (30-180 kVp, 2mA max)
Focal spot	0.5-2mm	0.6 - 10 microns
X-ray Interaction	Dominant-Compton Scattering Secondary - Photoelectric effect	Dominant-Photoelectric effect Secondary - Compton scattering
Resolution	.3-.5 mm	1-50 microns
Detector	Mostly solid state	Image intensifier and CCD or flat panel
Output	12 bit converted to Hounsfield Units	16 bit grayscale
Footprint	3X3 meters shielded room	Typical less than 1 sq. meter shielded container
Common Artifacts	Beam hardening, positioning	Ring, cone penumbra
Data Grid	512 X 512	2048X2048