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BENEFITS OF HIGH RESOLUTION COMPUTED TOMOGRAPHY IN CORE ANALYSIS

Michael Dixon
Omni Laboratories, Inc.
2501 Central Parkway, Suite C-13
Houston, Texas 77092

ABSTRACT

Medical computed tomography systems, or CAT scanners, are being used with increased frequency to nondestructively evaluate core samples. Most medical CAT scanners, however, have spatial resolutions on the order of one millimeter, which restricts the applications that computed tomography can address in core analysis. A new generation of computed tomography technology has been developed specifically for inspecting non-medical objects and industrial products. Some of these new industrial computed tomography (ICT) systems can provide greatly improved spatial resolution, approaching 0.05mm. These ICT systems can also provide high resolution images with relatively high source radiation energies of 420 KeV to allow nondestructive evaluation of large and dense core samples. Examples of new core analysis capabilities provided by high resolution ICT systems include screening of core plugs and whole core for relatively fine inhomogeneities, microfractures/induced fractures, and characterization of preserved and sleeved plugs.

INTRODUCTION

Medical CAT scanners have been used for nondestructive examination of core samples since approximately 1980. Currently there are more than 30 scanners in use in the petroleum industry. These scanners generate cross-sectional image density maps, or slices, through an object by rotating an x-ray tube around the object and obtaining views, or projections, at different angles. The cross-sectional image is then formed by reconstructing these multiple viewing angles in a computer. The computer can also assimilate and reconstruct a series of two dimensional slices into a three dimensional image.

Medical computed tomography scanners have been used in the petroleum industry for a variety of applications. The most common historical applications of these systems have been to identify artifacts due to coring, to characterize core material by detecting mineralogic and textural variations, and image core-flood results in three dimensions. Other applications include the characterization of natural fracture frequency, as well as orientation and the measurement of porosity in some rock types.

In 1977 a group of research scientists at the University of Texas began to develop hardware and software specifically designed to perform computed tomography on complex objects and industrial parts, rather than human bodies. The objective of developing an Industrial Computed Tomography (ICT) scanner was to provide improved image quality of a variety of objects at relatively higher source energies than medical systems. Today's ICT systems are being used with increased frequency for quality control in the aerospace industry, due to their high spatial resolution capabilities. Additionally, these ICT systems have the ability to image dense and complex objects, as well as provide precision measurements of internal features in a wide range of objects.

SET-UP AND DATA ACQUISITION

The objective of this study was to define the advantages and limitations of ICT technology for core analysis. A limited group of various core types were scanned on an ICT system. The sample types included consolidated sandstones, unconsolidated sandstones and carbonate rock types in the form of 4" core segments or plugs.

Inspections were made on a Scientific Measurement Systems, Inc. Model 101B+ Industrial Computed Tomographic (ICT) Analyzer. This analyzer is equipped with a 420 KeV x-ray source, a detector subsystem, computer subsystem, and an object positioning unit, which positions the object to be inspected between the source and detectors. Each discrete detector in the linear detector array can be collimated in the vertical and horizontal direction from 1.0 mm to approximately 0.05 mm.

Digital radiography is performed initially on each core sample to identify locations for selective computed tomography scans. Whole core and plug samples are placed on the object positioning unit table with the axis of each cylindrical sample oriented vertically. The sample is then passed vertically through the horizontal x-ray fan beam. It is necessary to make a series of vertical passes of the sample through the fan beam with a slight translation (movement of the object parallel to the linear detector array) of the sample to "fill-in" the interdetector spaces.

The resultant radiogram is constructed and is presented as a digital image with 256 grey levels. This image is "scaled" to view either the lower opacity edges of the cylinder or the higher opacity center. A horizontal-averaging image processing technique is then performed to minimize effects of changes in opacity due to the sample's cylindrical shape. After this processing, the radiogram can be used for screening essentially 100% of the core sample for overall density and atomic number variations. Some artifacts due to the horizontal averaging technique may occur if the core or plug is not a perfect right cylinder and it's edges are not truly vertical.

Computed tomography is performed after digital radiography at selective locations of the sample. The radiogram can be used to select CT slice planes, or tomograms are prepared at the top, middle and bottom of each sample when the radiogram appears relatively homogeneous. Some CT core analysis applications may dictate complete high resolution CT of a core sample. Such studies typically require a comprehensive three dimensional characterization of the sample and also should not have stringent time restraints. A tomogram is prepared on an ICT system by using rotate-only (3rd generation) or rotate-translate (2nd generation) methods. Both techniques generate a cross-section density map by obtaining a series of angular "views" within a plane of the sample. The rotate-translate method can provide better statistics at the expense of longer scan times, relative to the rotate-only method. The rotate-translate CT method is most commonly, used in this study.

The scanning parameters used on an ICT system can be optimized for a given application. The majority of the CT images in this study were prepared using 420KeV/3.0mA x-ray source with .042 lead filtration. Detector aperture settings were selected based on the desired image resolution and contrast sensitivity. The average detector aperture size was 0.25 mm (horizontal and vertical). Other scanning parameters used include an average ray spacing of 0.1 mm and an observation time of 0.01 seconds. The total scan times (per tomogram) represented in this study range from 1.5 minutes to 18 minutes.

STRUCTURE, MINERALOGY, AND POROSITY CHARACTERIZATION

The improved spatial resolutions inherent in an ICT system produce more spatially accurate images of core samples. A 4" core of a highly silicified conglomeratic rock type was initially scanned on a medical CT system (Deltascan 2020HR). This is the only core sample in this study which was scanned on a medical CT system and serves as a comparison with ICT results. A representative tomogram of this sample is shown in Figure 1, however the image quality has been reduced due to the photo reproduction methods used to generate this image. The black band through the center of the image is due to scanning through a plug hole. This image does demonstrate, however, the high signal-to-noise and contact sensitivity of this system.

A tomogram of approximately the same slice plane was prepared on an ICT system and is shown in Figure 2. A comparison of Figures 1 and 2 reveals the noticeable improvement of image quality due to improved spatial resolution of the ICT system. The edges of relatively large pores are well resolved and pores as small as 0.1 mm in diameter are detected. Also note the improved definition of the pyrite, which appears as the whitest feature in the ICT image. The contrast sensitivity of the ICT image, however, is lower than that exhibited by the medical CT image.

Figure 3 shows a representative tomogram of a 1" plug from the Berea Sandstone. The fine parallel bedding structure is well defined in this image. Note the patches of fine carbonate cement which appear as relatively white spots evenly disseminated in this cross-section. Over-sized secondary dissolution pores (black features) are observed and finer dissolution pores are more abundant in selective laminae. The box indicates the location of the enlargement in Figure 4. This enlargement is the result of reconstruction of the original CT data and is not a photographic enlargement. The enlargement shows dense, well cemented laminae which alternate with more porous laminae. The more porous regions contain relatively high amounts of secondary dissolution porosity with some of the larger pores approaching the fine sand grain size.

A digital radiogram and a representative tomogram of a 1" silty, very fine-grained sandstone plug is shown in Figure 5. A digital radiogram is basically a "shadowgraph" showing the entire density variation through a core sample as viewed from the side. The uneven shading of the digital radiogram is due to applying the horizontal averaging image processing to a plug which is not oriented at a true right angle to the scanning table. The radiogram indicates the presence of a high density and/or high atomic number mineral which is evenly distributed throughout the sample. Other analyses found this mineral to be halite. The radiogram does not provide information regarding the three dimensional distribution of this mineral within the plug. A tomogram was prepared at the slice plane location indicated by the horizontal line in the radiogram. The tomogram reveals a vague discontinuous bedding and the distribution of halite (white regions) within the plug, as well as on the surface of the plug.

CHARACTERIZATION OF FRACTURES

Figure 6 shows a digital radiogram (lower right) and a series of three tomograms of a 1" plug from an algal limestone. The location of the slice planes for each respective tomogram is shown with the radiogram. Algal structures appear in the radiogram as relatively low density features predominantly in the upper left and lower right areas of this image. The tomogram reveals several fractures which are filled by a relatively higher density mineral than the surrounding matrix. The filled fractures are oriented oblique to the axis of the plug and appear to represent at least two generations of fracture filling. Calibration of CT number and mineralogy could provide a means of extracting compositional information from these CT images.

Figure 7 shows a digital radiogram (lower right image) and three tomograms of a fractured carbonate core with a 4" diameter. The location of the tomogram slice planes are indicated with the radiogram. The radiogram shows the general relationship between the dominant vertical fractures and the subhorizontal, discontinuous lenses of "matrix" porosity. The fractures are essentially perpendicular to these porous lenses. The tomograms provide high resolution cross-sectional images of the porous and less porous regions of the core. The overall size, shape, and distribution of porosity is shown, as well as the degree to which fractures intersect "matrix" porosity. The orientation of fractures and other features can be readily determined from CT data on oriented core samples.

IDENTIFICATION OF CORING AND SAMPLING ARTIFACTS

Medical scanners have been used in the past for the identification of artifacts due to coring or sampling a core. These artifacts include induced fractures, mud invasion, and missing sections of core. The improved resolution and image quality of ICT systems allow detection of smaller artifact features (e.g. fractures, drilling mud), as well as accessing different types of artifacts such as thin gaps in sleeved plugs and extent of damage in sidewall cores.

A digital radiograph and tomogram were prepared from a 1.5" diameter plug sample of unconsolidated core intervals and is shown in Figure 8. The plug was enclosed in aluminum foil and plastic. The tomogram slice plane location is indicated on the radiogram. The radiogram reveals several subparallel fractures near the top of the image as well as scattered internal voids which were probably induced while cutting the plug. The radiogram also indicates the presence of scattered high density material and relatively large clasts near the base of the plug. The finely disseminated high density material was found to be fossil fragments by subsequent thin section analysis. The upper left image is the tomogram which is scaled to show the internal mineral and porosity distribution. Note the large scale voids and the fine concentric fractures on the left side of this image which represent damage due to plugging this soft sediment. The same tomogram is rescaled to show the foil wrapping material which appears as a grey component surrounding the plug. This tomogram shows a thin annulus between the wrap and plug on the left side of the image, as well as a more substantial gap in the upper left region. The resolution of this image even allows one to see the individual foil layers on the left side. This type of inspection procedure can be applied to unconsolidated core plugs sleeved in almost any material or to whole core sections encased in PVC, rubber and aluminum liners. Cores in steel collars can also be inspected by using a 420 KeV x-ray source on the ICT system.

Test scans were performed on a percussion sidewall core from the Cotton Valley Formation. Figure 9 shows a digital radiograph (lower right image) and three tomograms which were prepared with the sample in its unopened bottle. The location of the respective tomograms are shown in the radiogram. The tomogram in the upper left was prepared along the axis of the sample. Several features related to sample damage due to percussion sidewall coring are observed. These features include large scale fracturing and voids. Most of this well cemented sandstone has been pulverized during coring resulting in the micro-fracturing of cement and individual sand grains, as determined by thin section analysis. The relatively large high density areas shown in the upper left and upper right tomograms represent less than 10% of the total sample being relatively undamaged. This type of CT screening can be beneficial for sampling and selecting appropriate analyses on very limited sample material.

CONCLUSIONS

Limited studies of core samples using an ICT system have identified beneficial applications, as well as limitations of the technology. Improved spatial resolutions proved advantageous for characterization of relatively fine pore systems and identification of very subtle coring artifacts. The integrated use of digital radiography and computed tomography provides a rapid screening tool for plugs and core segments. The use of 420 KeV source energies provide the advantage of inspecting multiple cores and making longitudinal scans (parallel to core axis). Moreover, ICT image processing software can reduce image artifacts and enhance resultant image quality. The advantages of ICT systems compliment medical CAT scan capabilities, particularly for "difficult" sample types, by offering improved image quality, occasionally at the expense of inspection time. Disadvantages of high resolution tomography include relatively longer inspection times and higher equipment cost.

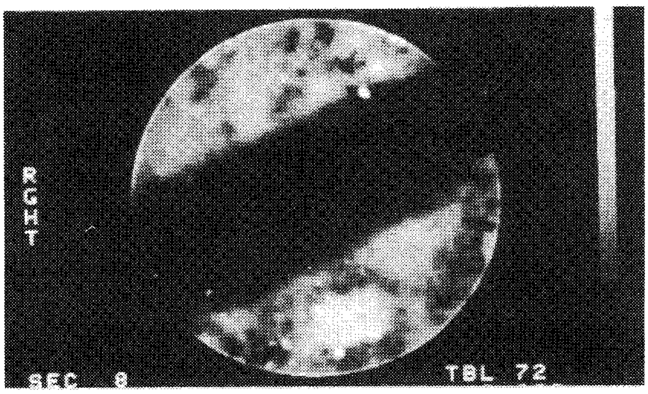

Figure 1. Representative tomogram through a plug hole in a 4" silicified core prepared with a medical CAT scanner.

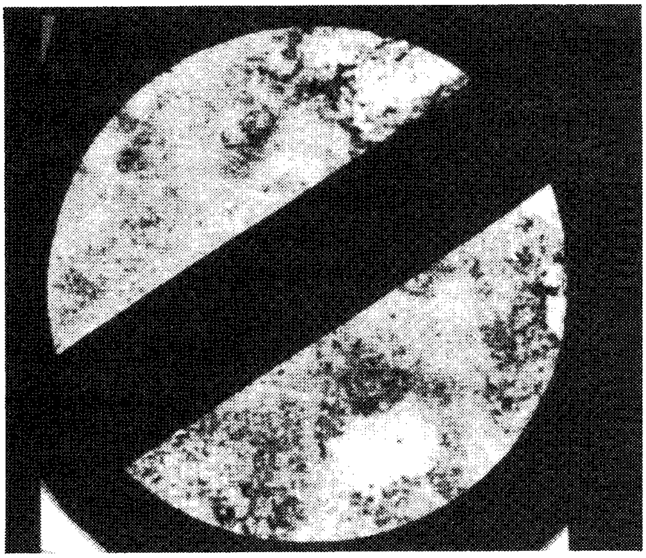

Figure 2. Tomogram at approximately the same plane in the core sample shown in Figure 1 prepared using an ICT scanner.

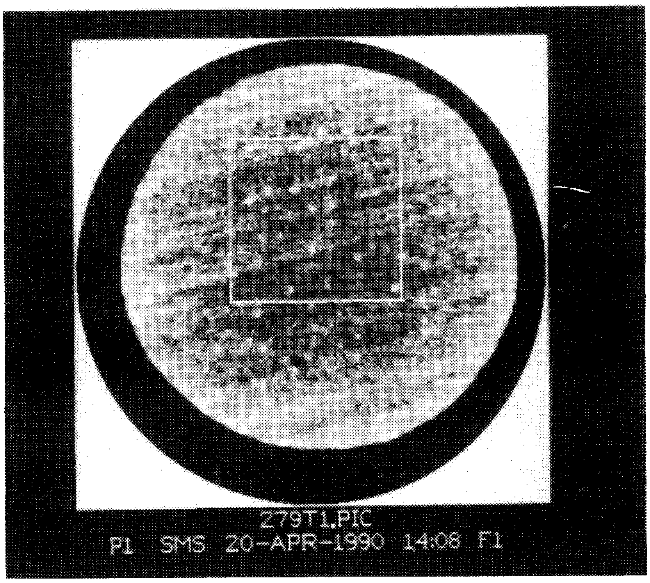

Figure 3. Tomogram of a 1" Berea Sandstone plug with box indicating the location of the enlargement in in Figure 4.

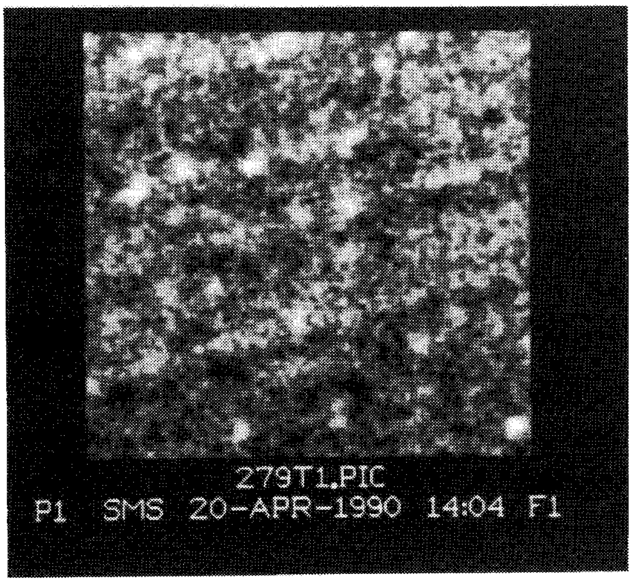

Figure 4. Enlargement of tomogram in Figure 3 showing pores and minerals as small as 100 microns.

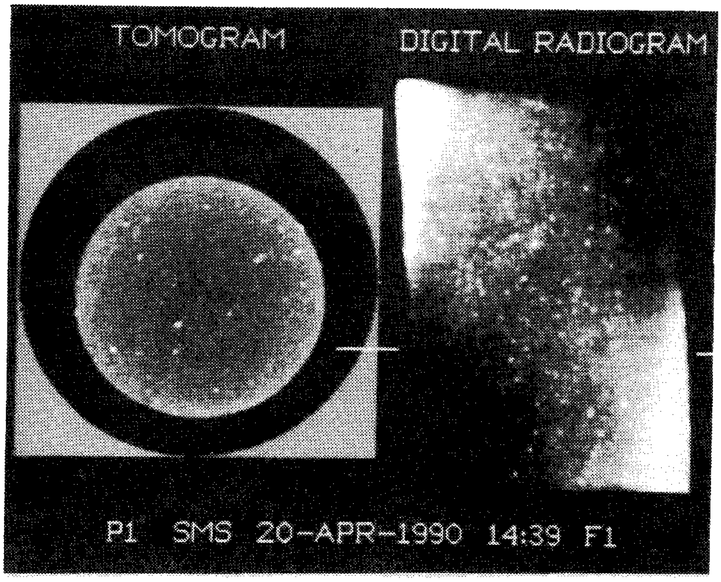

Figure 5. Digital radiogram (right) and representative tomogram (left) of a silty, very fine-grained sandstone with halite.

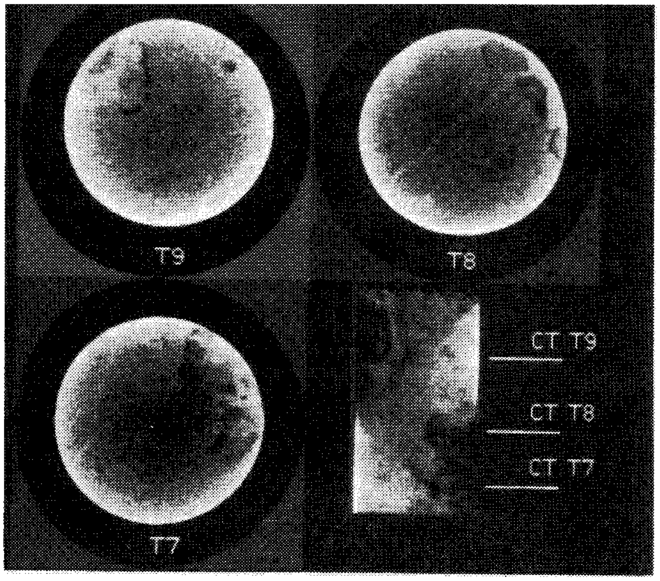

Figure 6. Digital radiogram (lower right) and three tomograms showing filled fractures in a 1" algal carbonate plug.

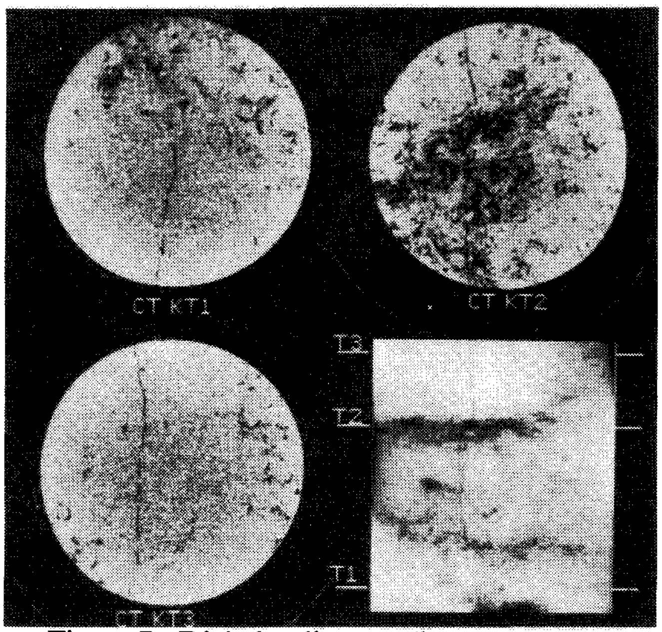

Figure 7. Digital radiogram (lower right) and three tomograms of a 4" fractured carbonate core.

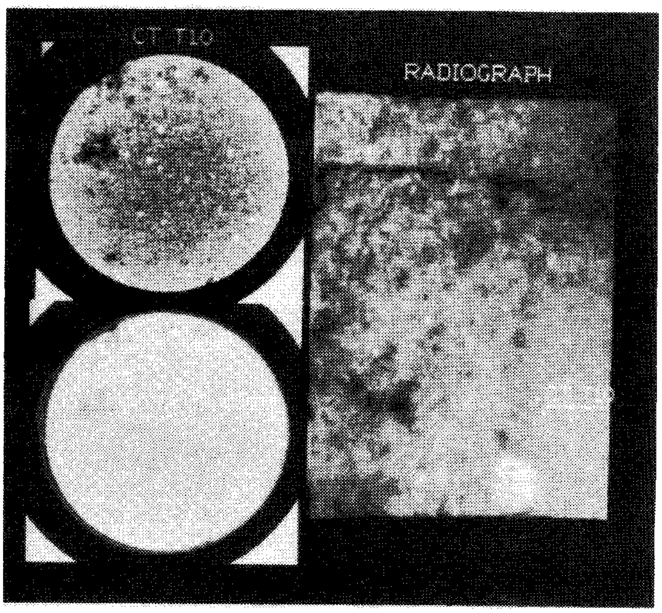

Figure 8. Digital radiogram (right) and a tomogram of a 1 1/2" unconsolidated sandstone plug showing sampling artifacts.

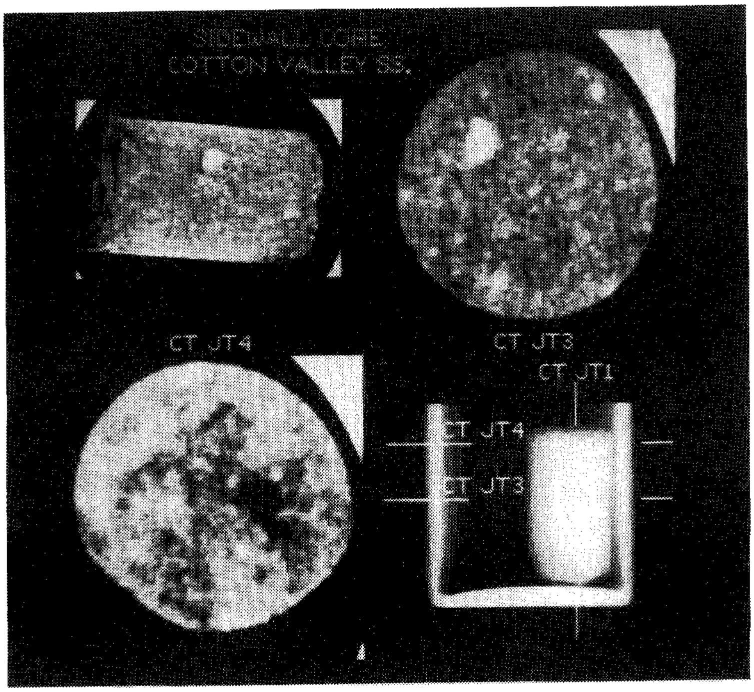

Figure 9. Series of tomograms and a digital radiogram (lower right) of a percussion sidewall core showing approximately 10% relatively undamaged material.