Application of Non-Destructive Continuous Motion X-Ray Analysis for Petrophysical Reservoir Characterization Studies

Gary Gunter[1], Kent Newsham[2], and Gene Kullman[3]

[1]NExT, [2]Petrophysicist, [3]IKONAS Technology Imaging

ABSTRACT: Case studies are used to illustrate the value of applying continuous motion x-ray analysis for selecting routine, special core analysis, and geomechanical core samples for subsurface evaluations. This technique has been successfully used on a wide range of petrophysical rock types including unconsolidated reservoirs, high porosity chalks, low permeability systems, naturally fractured reservoirs and mixed lithology systems.

Continuous motion x-ray analysis or digital fluoroscopy is a non-destructive, inexpensive, and precise x-ray core imaging method. This process produces a real time continuous high-resolution core image that measures volumetric density contrast viewed through 360 degrees of rotation.

Fluoroscope imaging provides investigators the ability to visualize depositional and structural features within the internal structure of a sample. Continuous rotation of whole core or core plugs provides information on size, density contrast, spatial distribution and orientation of framework features. Often these events are visible in a narrow range of azimuths. Results show that it is common to find up to 50% of core plugs unsuitable for testing, because of small-scale heterogeneities such as micro fractures, fine scale faults, laminae, and burrowing. When extracting core plugs from conventional cores in directional wellbores, proper orientation of the core plug is simplified by using the full motion fluoroscopy method. This technique is complimentary to X-Ray Computed Tomography.

Screening core samples for internal consistency with the fluoroscopy method significantly reduces the uncertainty associated with laboratory measurements. Thus, interpretations can apply the measurement results with a greater degree of confidence. These images are cost effective and improve subsurface evaluation cycle time. Repeat measurements due to poor sample integrity is costly to both the vendor and sponsoring asset team. Our results show that improved sample quality control, selection, improved subsequent measurement precision, and effective cost control are essential elements for securing management support to obtain laboratory data.

INTRODUCTION: A number of challenges face the core analyst in extracting core plugs for routine and special core analysis. Plug orientation and the internal integrity of the extracted plug have a profound impact on the quality and validity of any subsequent measurements. Attaining the proper plug orientation relative to bedding and apparent dip in deviated boreholes can be difficult without first slabbing the whole core. Slabbing the core such that the maximum dip of the internal structures is exposed on the slab also requires knowledge of the internal structural orientation. Unfortunately, the bedding dip is not always self evident from the observation of the pre-slab whole core. Internal flaws, whether natural or induced by the extraction method, may invalidate the plug as a candidate for special core measurement. As an example, use of a plug with open fractures, that is destined for electric properties or relative permeability testing will result in measurements that are not representative for evaluation purposes. In all of the above cases, the use of continuos motion x-ray analysis or fluoroscopy can aid in solving these challenges. Using fluoroscopy to examine the internal structures of a core before slabbing, plugging, and prior to testing of individual samples can result in significant project cycle time reductions, cost saving, and improved measurement results. This is a tool that provides for better management of project uncertainty.

Historic Experience – Core analysis programs pre-dating the 1980's, often excluded any form of core or plug quality control checks for internal integrity, depositional and structural features. In the 1980's and 1990's, computer tomographic x-ray techniques became more available to the industry, but generally limited to two-dimensional imaging. Full three-dimensional tomography is expensive and not often employed. CT scanning methods provide static, high resolution, two dimensional, cross sectional image of the core cylinder. These images are typically captured with an orientation along the sample longitudinal axis at varying azimuths and in a radial orientation, perpendicular to the sample longitudinal axis and at varying distances along the sample length.

Commercial labs invoice the CT acquisition in one of two ways; a unit price per foot with a fixed number of longitudinal and radial images, or by invoicing a unit price per image. A limitation of the CT Scanning method is that only a small volume of rock over a small subset of azimuths is sampled under these pricing structures. Where complex sedimentary structures, oblique bedding orientations, and internal sample flaws exist, the CT Scanning method may not provide a full characterization of these attributes, unless an extensive and costly imaging program is completed. However, CT Scanning used in conjunction with continuous motion fluoroscopy is a powerful combination. In the event that continuous motion x-ray identifies a feature that needs further examination, we recommend that a detailed CT image should be obtained. This is especially true if the sample is being considered for displacement testing, geomechanical analysis, electric properties, or formation damage studies. The continuous motion fluoroscopy technology is an inexpensive but precise x-ray core-imaging alternative. High-resolution images of the core sample's internal structure can be viewed through 360 degrees of rotation and recorded on videotape. Since the entire sample volume is imaged, this yields an image that reflects an accurate spatial relationship of any observed features within the core sample.

DISCUSSION: *Applications* – The uses of core imaging are independent of the acquisition method, however, it has been found that the fluoroscopy method provides superior imaging in the following applications.

1) Imaging the internal bedding structure to properly orient the whole core to attain the maximum dip in the slab end, before slabbing the whole core.
2) Imaging the apparent dip in deviated core for proper plug orientation, either vertical or horizontal plugging.
3) Imaging zones of shear failure in the core at the core barrel joints. Often, torsion fractures are induced in the core while breaking down the core barrel at the joint. These intervals may be shattered and inappropriate for either routine or special core sampling.
4) Imaging whole core for fractures, bed orientation, and other flaws in advance of plugging to maximize plug recovery and integrity.
5) Imaging core plugs for internal flaws such as open fractures, micro-deformation bands, or gas expansion fumaroles as a quality control step. This is critical for any special core analysis candidate, as these flaws could invalidate the measurement from an interpretation standpoint.
6) Geologic interpretation of sedimentary structure and orientation, if from an oriented core.

The economic viability of using an imaging program on a core study can be determined by a good ‘rule of thumb’. If the cost of the core measurement is five times greater than the cost of the imaging, then the imaging process is cost effective in screening poor quality plugs from the core data acquisition program.

X-Ray Equipment – The continuous motion, digital fluoroscope system X-rays are generated using a TFI Gemini II industrial x-ray tube emitting x-rays in the range of 18 to 159 KVP at 1 to 30 milliampere. The x-rays are passed through the core sample held within a carrier system that simultaneously moves the core through the x-ray beam while rotating the core 360 degrees. A two-dimensional x-ray image of the core is converted to a two-dimensional light image using a Mackell Dynavison visible light intensifier. This light image of the core’s internal features is picked up by a video camera and displayed in real time on a video monitor and recorded to a digital format using a microprocessor. The rate of movement is operator controlled, whole core is generally conveyed at a speed of 4 feet per minute and a rotation of four revolutions per minute for whole core. Core plugs are processed at much slower rates and placed into an adapter for 1”, 1.5”, or 2” diameter samples. The output image is captured at no less than one frame per degree of rotation.

General X-Ray Response - Internal features of core are observed with an X-ray fluoroscope because of differential spatial attenuation of the energy beam as it passes through the core material. The amount of x-ray attenuation within a core is a function of the following intrinsic properties:

(1) core porosity (2) core bulk density (3) mineral constituents (4) pore fluid type and distribution.

If all these parameters were uniform throughout the core, then uniform spatial attenuation would occur, resulting in no image or more specifically, a uniform gray level image (Figure 1). If any or all these parameters vary spatially, then the resulting x-ray image will show the dark images as areas of high attenuation and the light images as areas of low attenuation.

In core samples, these properties occur in such a way that the overall morphological character of the variations are recognizable as internal features, such as bedding laminae, burrows, fractures, localized mineralization, fluid distributions, mechanical damage, and other small scale heterogeneities (Figures 2,3L, and 3R).

Continuous Motion –The sample is continuously rotated in such a fashion as to completely image any internal feature. This provides valuable information to the investigator over conventional static techniques. Results show that a rotation of a sample by as little as one or two degrees can cause an image of an internal feature in the core to disappear from the output image. Therefore, 360 degrees of rotation is necessary in order to provide a complete investigation for small-scale heterogeneities.

Case Study Examples – In the following fluoroscopy examples, the volumetric density contrasts are shown as gray scale images. ‘Positive’, white images represent low attenuating events such as open fractures.

Figure 1 is an example of a 1” diameter, vertical plug with fairly uniform internal properties. Little contrast is detectable within the plug as seen by the uniform gray scale image. The black dot in the center of the plug is an aiming target. The dark band towards the bottom is a clay lamination. This plug would be an excellent candidate for any core testing requiring a vertical plug orientation.

Figure 2 stands in contrast to Figure 1, as an example of a vertical plug with very heterogeneous internal properties. The plug is a 1” diameter sample and the orientation is approximately 30 degrees to bedding. The oval events are dense, mud-filled burrows. There is a near horizontal, styolitic event that is also dense. This plug did not pass the integrity criteria for further core testing.

Figure 3L is a classic example of what can happen to core material containing light hydrocarbons that are decompressed too rapidly from the subsurface. The ‘dendritic’ pattern on this vertical plug is a result of gas expulsion while the core was brought to the surface resulting in the internal fractures. This plug looked fine based on external observation. However, this plug is unacceptable for further testing other than for grain size and mineralogy analysis.

Figure 3R is an example of a vertical plug with very subtle induced fractures and a micro-fault. Both events appear to be mud invaded with barite, yielding the dark lineaments. The micro-fault (red arrow) was observed only through a range of 15 degrees of azimuth and could be easily missed without the full motion and rotation during imaging. The induced fractures (blue arrows) show a spiral distribution when viewed spatially, indicting that a torsional force created these fractures. All of these features could cause extreme perturbations in special core testing.

Impact Of Screening Core Samples Used Within Subsurface Evaluations – Continuous Motion X-ray Analysis was applied in an extensive geomechanical core program to aid in screening plugs before initiating laboratory compression tests. This evaluation required sampling a broad range of rock types and rock strengths. Over 600 one-inch diameter vertical core plug samples were extracted from 1000 feet of whole core. Half of these samples were discarded due to visible flaws. The remaining 300 samples appeared to have sufficient sample integrity for compression testing. Since the average cost of geomechanical testing for the complete sample set approached $150,000.00 USD, it was decided to fluoroscope the entire 300-sample set. The goal was to improve the sample quality; hence the precision in the test results, by eliminating samples with internal heterogeneities. As an example, if a plug contains internal fractures, the result of a triaxial compression test will be to measure the yield strength of the fracture rather than the intrinsic strength of the rock frame. The total cost of the fluoroscopic survey was less than 10% of the cost of the proposed compression tests. Of the 300 samples that were fluoroscoped, 150 were found to be inappropriate for testing due to improper orientation to bedding, open fractures, or other heterogeneities considered not representative of the rock. Thus, 450 samples from the original 600 were eliminated for geomechanical testing due to sample heterogeneity.

The improved precision in geomechanical testing results is inferred in the Figures 6a, 6b, 7a and 7b. Figures 6a and 6b are derived from triaxial compression tests performed by Jason Zhang (Zhang, 2000). Figure 6a is a plot of mean stress $(\{\sigma1+\sigma2+\sigma3\}/3)$ versus differential stress $(\sigma1-\sigma3)$ for a series of triaxial compression tests completed on a suite of rocks. No sample screening was performed in advance on these compression tests. Figure 6b is a translation of Figure 6a into pseudo-pressure space (each axis is divided by the critical pressure of each sample measured) to create the Zhang ‘Universal Failure Criteria’ (Zhang, 2000). Note the fair amount of dispersion in the results along the curve-linear trend line of Figure 6b.

Figures 7a and 7b display the results of the geomechanical tests performed on the sample set that was screened using the fluoroscopic method. Figure 7a is equivalent to Figure 6a, showing the triaxial compression results, at varying confining pressures, in mean stress versus differential stress space. Figure 7b is equivalent to 6b, implementing the Zhang ‘Universal Failure Criteria’ method to the fluoroscoped sample set. Comparison of Figure

7b to Figure 6b shows that the results in Figure 7b have less scatter along the curve-linear trend line. This resulted in greater precision in the prediction of rock strength profiles based on the measured failure criteria.

The improvement in Figure 7b versus Figure 6b could be due to a number of factors inherent to the rock fabric. However, when plug quality control via screening is completed, results that lower project uncertainties have been obtained.

CONCLUSION: Applying this technique for subsurface petrophysical or reservoir characterization has demonstrated many benefits. The small-scale heterogeneities that are identified often occur over a narrow range of azimuths. In most cases, these events often would not be identified except as an anonymous laboratory data point. Eliminating these samples means improved project cycle time and fewer laboratory re-tests.

Continuous motion x-ray analysis or digital fluoroscopy used in conjunction with computed tomography imaging provides valuable information that otherwise is difficult to obtain. Fluoroscopic imaging provides investigators a non-destructive method to visualize depositional and structural features within the internal volume of a sample.

The case study shows that only 150 samples from the original 600 samples were suitable for geomechanical testing. In our opinion, imaging is a necessary quality control step before laboratory measurements are initiated.

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We would also like to thank our respective management teams for providing the opportunity to present this work.

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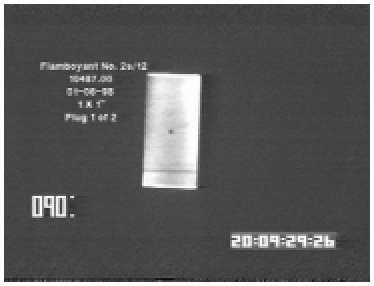

Figure 1. A good example of a core plug with homogeneous properties that would be a candidate for special core testing. The horizontal band towards the bottom is a lamina of clay.

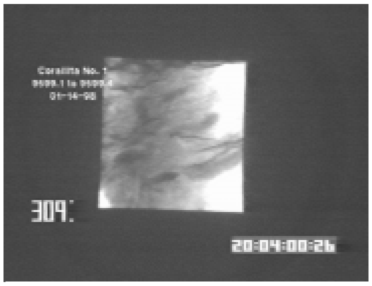

Figure 2. An example of a core plug with very heterogeneous properties. The oval events are mud-filled burrows oriented at 30 degrees to bedding.

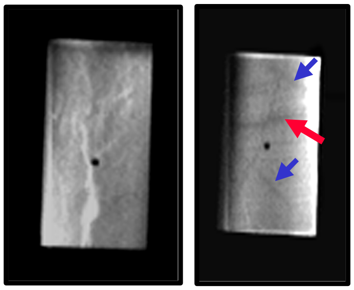

Figure 3L. This vertical plug shows a 'gas fumarole. Figure 3R shows an internal "fracture" that is a micro-fault. These features are noted when viewed in 360 degrees of rotation

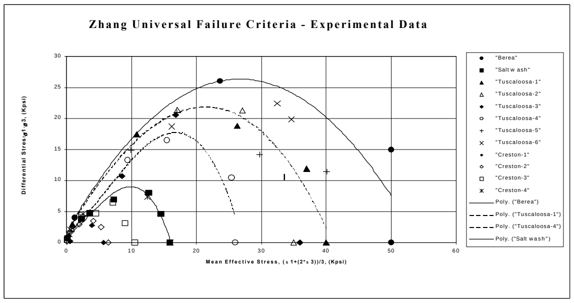

Figure 6a is a plot of mean stress versus differential stress for a series of triaxial compression tests completed on a suite of rocks. The curve linear lines represent the failure criteria for a given suite of rocks sampled from the same depth interval.

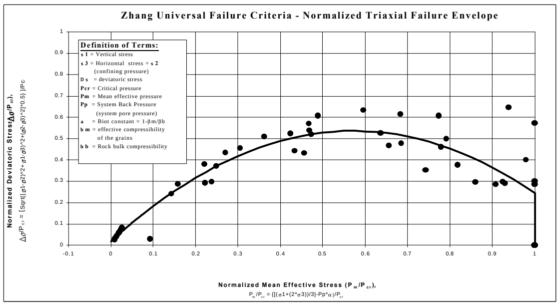

Figure 6b is a translation of Figure 6a into pseudo-pressure space (each axis is divided by the critical pressure of each sample measured) to create the Zhang 'Universal Failure Criteria' (Zhang, 2000). Note the fair amount of dispersion of the translated data in the range from 0.1 to .5, pseudo-mean effective stress (the x-axis).

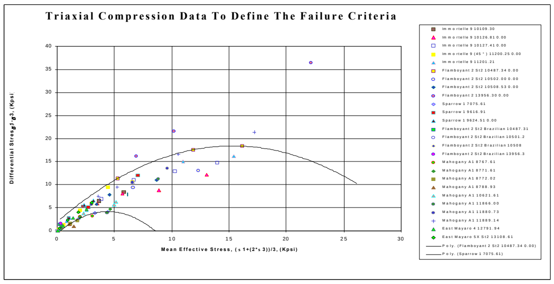

Figure 7a is a plot of mean stress versus differential stress for a series of triaxial compression tests completed on a suite of rocks that were inspected using the continuous motion fluoroscope. The curve linear lines represent the failure criteria for a given suite of rocks sampled from the same depth interval.

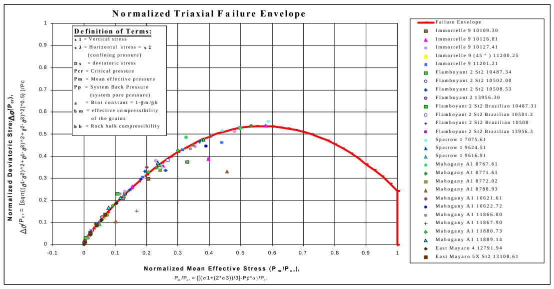

Figure 7b is a translation of Figure 7a into pseudo-pressure space to create the Zhang 'Universal Failure Criteria' (Zhang, 2000). Note that the reduced amount of dispersion of the translated data in the range from 0.1 to .5, pseudo-mean effective stress (the x-axis), when compared to Figure 6b. This improved precision will yield better rock strength profiling results.