NEW X RAY SCANNING SYSTEM FOR SPECIAL CORE ANALYSES IN SUPPORT OF RESERVOIR CHARACTERIZATION

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ABSTRACT

This paper describes a newly constructed dual-detector x ray scanning system for coreflood fluid saturation and rock heterogeneity measurements. The system was built for scanning cores and fluids during high temperature, high pressure reservoir-condition tests. Examples of reservoir characterization applications that have benefited from its use are presented, including two- and three-phase saturation measurements and rock heterogeneity detection. The scanning system combines advantageous features of imaging and linear x ray scanners.

The x ray scanner is especially useful for routine and reservoir-condition special core analyses in support of reservoir characterization. Coreflood experiments are attached to a 2 m tall by 3.6 m long sample rack that has a 1 m high by 3.1 m long x ray scan region. Several experiments can be performed concurrently. The 7.5 to 160 kV x ray tube has 2 focal spots - a 0.4 mm focus that is used for imaging and a 3 mm focus that is used for x ray intensity measurements. The tube is mounted in front of the sample rack on a platform. A germanium detector and an image intensifier are mounted to a detector platform, which is positioned opposite from the tube on the other side of the sample rack. X ray intensity and energy measurements from the germanium detector are used in determining two- and three-phase fluid saturations within rock plugs during flow tests. The image intensifier provides live x ray images of rock and fluid features. The tube and detector platforms move parallel (horizontal and vertical) and perpendicular (in and out) with respect to samples mounted to the sample rack. For three-phase saturation determinations using the germanium detector, provisions are included to automatically collimate and filter the x ray beam. A rotating platform is also affixed to the sample frame to allow samples to be rotated while x ray images or data are recorded. Data acquisition and control are via a laboratory PC. Advantages of scanner X-Y-Z control with and without sample rotation are discussed.

BACKGROUND

We needed a versatile x ray scanner for reservoir-condition special core analyses. Desired attributes were the flexibility and accuracy of a linear x ray scanner for point-measurements of multiphase fluid saturations along horizontal or vertical traverses across cores, and the ability to generate rapid x ray images or radiographs revealing rock heterogeneities and how they affect fluid distributions in rocks.

The use of an x ray device to determine fluid saturations in rocks and to describe rock heterogeneities is not new. There are many descriptions in the literature describing linear x ray scan techniques for determining two- and three-phase fluid saturations in rock samples during laboratory corefloods; some of which are provided in references 1 through 14. Combined horizontal and vertical scan capabilities offer distinct advantages.[14] X ray CT scanners have been used to provide descriptions of saturation distributions and rock heterogeneities. For examples, see references 15 through 18. However, we did not find descriptions for a multi-purpose scanner that combines useful attributes of both linear x ray and imaging x ray scanners.

Linear scanners and imaging scanners are typically built according to widely different sets of design constraints. Particular differences between linear and imaging scanners include types of x ray tubes employed; tube voltage and current ranges; exposure times; x ray beam conditioning and collimation; types of detectors employed; movements and spacing. No commercially available scanner was found that would meet all of the expectations that we had for this device. For this reason, we had this unique instrument designed and constructed.

HARDWARE AND OPERATION

The scanner (figure 1) consists of a tube platform and a detector platform that move on opposite sides of a center sample rack. Coreflood experiments are mounted on the 2 m tall by 3.6 m long center rack. The portion of the center rack that can be x ray scanned is 1 m high by 3.1 m long. This large scan region accommodates many experiments that can be scanned concurrently. The extruded aluminum framework is easy to assemble and reconfigure to adjust for different types of experiments.

The scanner uses a Philips Industrial X-ray (now Yxlon International) MG325 system with a 165 kV metal ceramic x ray tube. The tube is mounted in front of the sample rack on a platform. The tube has a 3 mm focus that is used during x ray intensity measurements and a 0.4 mm focus that is used during imaging scans. The standard focus and fine focus capabilities provided by this x ray tube were key to building the multi-purpose scanner. The tube potential can be varied from 7.5 kV to 160 kV. Tube current can be varied from 0.5 to 45 mA with the 3 mm focus and from 0.5 to 5 mA with the 0.4 mm focus. The broader current capacity of the 3 mm focus provides flexibility for adjusting x ray intensities while maintaining selected tube potentials. This flexibility is important for optimizing x ray settings in preparation for tests in which rock fluid saturations are calculated from x ray intensities. For imaging, the 0.4 mm focus provides better detail and sharpness than the 3 mm focus. The tubehead shield includes a lead shutter that opens when an exposure is in progress and closes afterwards. A collimator (lead shutter with center 5 mm hole) drops in front of the beam when germanium detector scans are in progress. Pneumatic positioners are also attached in front of the tubehead to automatically slide filters into the x ray beam path for scans in which beam conditioning is desired.

Two detectors are mounted on the detector platform; an Applied Optics Model PS92 image intensifier with a CCD video camera system for imaging, and a Canberra GL2020R low energy germanium detector with a multichannel analyzer for intensity and energy measurements. The dual-field image intensifier can be switched from 16 cm to 22 cm mode, gaining 150% electronic image magnification when desired. An X-Y shutter system is positioned in front of the image intensifier. The shutter is used to "clamp down" on the region of interest displayed by the image intensifier. The image intensifier and its video camera provide live x ray images of whatever the x ray beam penetrates, such as a rock sample within a coreholder or fluids within a fluid separator. Output from the image intensifier is routed to a monitor for display, a VCR for recording video, and a video acquisition board within the lab computer so that images can be captured and analyzed. A video typewriter is used to add text to x ray videos and images or to place reference marks on the monitor when using the scanner as a dimension measurement tool.

Lead caps containing slots of different widths or holes of different diameters can be placed in front of the germanium detector to affect the sample volume represented by a germanium detector measurement. The caps are designed to collimate or limit x rays that reach the detector to those that pass through a particular rock volume. This is done to resolve measurements to coincide with particular regions within the rocks. A slotted lead cover is horizontally oriented when samples are oriented vertically. The slot in the cover is vertically oriented when samples are oriented horizontally. A lead cap with a 2 mm diameter hole drilled through its center is used for scans with very tight position constraints.

The tube and detector platforms move parallel (horizontal and vertical) and perpendicular (in and out) with respect to samples mounted to the sample rack. The tube and detector platforms are coupled so that they always move together horizontally (X-direction). The range of motion for the X-axis is 310 cm with position resolution of 0.1 mm. Each platform is moved in the vertical direction (Y-direction) by its own stepper motor. Y-axis movement is over a range of 130 cm with position resolution of 0.1 mm. During normal Y-axis movements, travel for both platforms is synchronized and the x ray beam and selected detector remain aligned. The exception is when switching detectors. In this case, the Y-coordinate for the selected detector is first automatically aligned with the Y-coordinate of the center of the x ray beam. Thereafter, both platforms remain vertically aligned during Y-axis movements. Each platform has its own stepper motor for movement toward or away from the sample rack (Z-axis). Z-axis range of travel is from about 4 cm from the sample rack for both platforms to 85 cm for the tube and 76 cm for the detector (161 cm maximum distance between the tube and detector). Z-axis position resolution is 0.1 mm.

A rotating platform is also affixed to the sample frame to allow samples to be rotated while x ray images or intensity data are recorded. This platform is driven by a rotary microstepper motor and can be controlled to rotate between 0 and 360 degrees.

Data acquisition and control are via a laboratory PC. LabVIEW® and IMAQ® software from National Instruments is used for data acquisition, control, and image processing.

The scanner operator controls the scanner via the LabVIEW® application either through manually entering scan parameters or by running automatic sequences from a workstation outside of the lab in which the scanner resides. The x ray tube voltage, current, and shutter can be controlled either manually or via the LabView® application. The operator's console also includes two monitors that are linked to video cameras in the x ray lab. One monitor provides display from a video camera that is mounted next to the x ray tube on the tube platform while the second camera provides a full field image of the scanner and sample rack from a camera mounted on the wall of the lab. The walls, door, and windows to the x ray lab contain x ray absorbers to prevent x rays from penetrating to areas outside of the lab. Staff vacate the scanner room when scans are in progress. Interlocks and other safety controls are incorporated into the system to prevent accidental x ray exposure.

GERMANIUM DETECTOR SCANS

The germanium detector is principally used when measuring fluid saturations and their distributions within rock samples during laboratory corefloods. It is also used for checking the x ray absorption characteristics of fluids within fluid separators. Germanium detector scans can be set up for single-point measurements, point measurements at positions along one movement axis (such as a traverse across a sample from inlet to outlet), or point measurements according to a 2 parameter matrix (such as an X-Y grid or rotation and Y-axis movement scenario). Scan parameters including measurement coordinates, tube settings, beam collimation and conditioning, and intensity integration ranges are saved as automatic scanning sequences. Automatic scanning sequences can be recalled and repeated. Different scanning sequences can be run sequentially to scan different concurrent experiments.

Z-axis movement capabilities allow flexibility for moving the tube and detector platforms toward or away from samples to accommodate coreholders, heat chambers, and other devices of various sizes. The broad X- and Y-axis ranges provide flexibility when designing various types of coreflood experiments.

IMAGING

The image intensifier can be used for both qualitative and quantitative x ray measurements. When setting up scan parameters to identify particular rock features or to measure changes in fluid saturations, tremendous latitude is available for adjusting the X-Y-Z coordinates of the tube and detector, tube potential and current, and image processing routines for maximizing the amount of useful information that scans provide. This is in contrast to many petroleum laboratory scanners that were formerly used in medical applications.

As previously mentioned, the shutters in front of the image intensifier are used to "clamp down" on specific regions of interest. For example, figure 2 is an image of a chalk plug positioned on a glass frit within a Teflon centrifuge tube. The x ray image was obtained with low x ray tube voltage and current and fairly wide image intensifier shutter settings. The plug, water and oil interface, and portions of the centrifuge tube are shown. Higher photon energies are necessary to gain detail of plug features or saturation distributions within the plug. With the imaging set-up of figure 2, at significantly higher x ray tube energies, low x ray attenuation regions around the plug become so bright that the rock image quality is impaired and portions of the image intensifier are needlessly subjected to high x ray radiation. This condition is resolved simply by moving the X and Y image intensifier shutters inward to mask regions other than that of the plug. The x ray tube voltage and current are then adjusted to gain a clear image of the rock.

Figure 3 is an x ray image of the plug of figure 2. The presence of the burrow-like feature within the plug was unknown until the sample was x ray scanned. The graph to the right of the image shows variation in gray scale intensities along a vertical profile through the center of the image. This type of information is used in determining saturation profiles.

Figure 4 is an image of a 4.5 cm thick by 17 cm long slab of Bluejacket sandstone. Images such as that of figure 4 provide a quick means for identifying rock heterogeneities, bedding plane orientations, cracks, vugs, and other rock features. When a feature of interest is identified within a sample from a particular x ray view, the image can be captured as a TIF file for further enhancement, processing, or analysis. Although the image intensifier provides 2-dimensional x ray images, rotation can be used to gain a 3-dimensional perspective. Many features that are not apparent from visual inspections show up clearly on x ray images. Cracks and bedding planes become readily apparent as these features are rotated into alignment with the x ray beam.

By adding a reference mark on the image intensifier monitor using the video typewriter, the imaging system is very useful for measuring dimensions of samples, even while they are confined within coreholders and subjected to high temperature and stress conditions. To measure the length of a vertically positioned sample, one first adjusts the scanner Y-axis until the reference mark on the video monitor is positioned at one end of the sample. Next, the scanner is moved in the Y-direction until the reference mark is positioned at the opposite end of the sample. The length of the sample is found by the difference between the starting and ending scanner positions. This technique was used for measurements shown on figure 2. The ability to measure objects with precision to 0.1 mm is useful for quickly determining X- and Y-coordinates for germanium detector scans, for correlating pressure tap locations within coreholders with distances along the lengths of plug samples, and for determining changes in sample dimensions as a result of changing stress conditions. This approach is also used to rapidly measure fluid interface locations within 2- and 3-phase fluid separators during multiphase flow tests. Fluid interfaces are clearly distinguished even when oil, brine, and gas fluids do not contain x ray dopes. Live x ray images also reveal when droplets of fluids adhere to the walls of a separator, splash upon entering the separator, or form emulsions.

Images captured to the computer from the image intensifier consist of pixels arranged in 640 columns by 478 rows in 256 shades of gray. The pixel resolution for an imaged object depends upon how much of the image field is occupied by the object. This in turn depends upon the degree of magnification (up to 6X) provided by the image intensifier and by the Z-coordinate positions of the tube and image intensifier. Changes in the natural logs of gray scale pixel values from images are correlated to changes in fluid saturations within imaged rocks. Average gray scale values for entire images can be quickly determined using histogram functions. Saturation calibrations can be developed on a pixel by pixel basis for determining saturation distributions from images.

COMPARISON OF DETECTOR RESULTS

Table 1 provides data from a simple test to illustrate how germanium detector and image intensifier measurements compare for a simulated two-phase fluid system. The scanned sample was a 3.81 cm diameter chalk plug that was placed behind several plastic cells. X ray measurements were recorded after filling the cells with various thicknesses of air and brine. This type of set-up is useful for gaining a sense of optimal x ray settings in preparation for coreflood tests. The brine contained 7% by weight potassium iodide. Germanium detector and imaging scans were taken using the same tube and detector positions. Tube power settings, collimation, and other parameters were initially optimized for each type of scan. Thereafter, the settings were held constant for each series of x ray measurements. Data in table 1 are for a particular scan position.

As shown in table 1, data from both types of detectors are very well correlated with brine thickness in this case. In general though, a slight amount of noise in the data has a greater impact on accuracies of image intensifier saturation measurements than on saturations determined using the germanium detector.

APPLICATIONS

The most powerful feature of this scanner is being able to perform x ray intensity measurements and x ray imaging with the same unit. This ability is invaluable for assessing effects of rock heterogeneities on fluid flow patterns and fluid recoveries. Sample dimension measurements using the image intensifier simplify establishing starting and stopping positions and scan increments for germanium detector scans. Comparisons of live x ray images with the beam collimator on and off provide information about rock regions that are represented by germanium detector scans as well as guidance on how to best adjust the tube and detector Z-axes to obtain the best beam coverage for both small and large diameter plugs. The germanium detector can also be used to characterize x ray beam energies and intensities for determining effects of beam conditioning on image quality.

Two-phase fluid saturations can be determined either from correlations using intensity data from the germanium detector or by analyzing gray scale images. X-Y-Z axis movement controls provide flexibility for using the scanner to measure saturations in horizontal and vertical corefloods and to accommodate coreflood equipment of various sizes. The scanner can be used for measuring in-situ two- and three-phase saturations in core samples at reservoir conditions of temperature and pressure. The ability to measure three-phase in situ core plug saturations using the germanium detector and to immediately measure fluid volumes within the three phase fluid separator with the image intensifier has greatly simplified the design of a three-phase closed loop coreflood system. We've used the scanner to determine saturation distributions in centrifuged core samples, to identify fluid saturation changes in rocks during flow with and across fractures, to screen and select plugs for experimentation, to locate bedding, filled burrows, cracks, and other features in rock samples that are not readily apparent from visual inspection, for measuring porosity distributions in plugs, and many other applications. It has been a very useful tool for mechanistic modeling.

CONCLUSIONS

In conclusion, many benefits are gained from combining intensity measurement and imaging detectors on one laboratory x ray scanner. This ability is invaluable for assessing effects of rock heterogeneities on fluid flow patterns and fluid recoveries. Four degrees of freedom (X-Y-Z axis control plus rotation) provide opportunities for optimizing x ray measurements in support of special core analyses for reservoir characterization.

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REFERENCES

1. Boyer, R., F. Morgan and M. Muskat, "A New Method for Measurement of Oil Saturation in Cores", *Petroleum Transactions, AIME*, (1947) **170**, pp. 15-33.
2. Morgan, F., J. McDowell, and E. Doty, "Improvements in the X ray Saturation Technique of Studying Fluid Flow", *Petroleum Transactions, AIME*, (1950) **189**, pp. 183-184.

3. Laird, A. and J. Putnam, "Fluid Saturation in Porous Media by X ray Technique", *Petroleum Transactions, AIME*, (1952) **192**, pp. 275-284.
4. Laird, A. and J. Putnam, "Three Component Saturation in Porous Media by X ray Techniques", *Petroleum Transactions, AIME*, (1959) **216**, pp. 216-220.
5. Schneider, F. and W. Owens, "Sandstone and Carbonate Two- and Three-Phase Relative Permeability Characteristics", *Soc. Of Petr. Eng. Journal*, (March 1970), pp. 75-84.
6. Schneider, F. and W. Owens, "Steady-state Measurements of Relative Permeability for Polymer/Oil Systems", *Soc. Of Petr. Eng. Journal*, (February 1982), pp. 79-86.
7. Oak, M. and R. Ehrlich, "A New X ray Absorption Method for Measurement of Three-Phase Relative Permeability", Paper SPE 14420 presented at the 60th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, Las Vegas, NV, (Sept. 22-25, 1985).
8. Oak, M., L. Baker, and D. Thomas, "Three-Phase Relative Permeability of Berea Sandstone", Paper SPE/DOE 17370 presented at the 1988 SPE/DOE Symposium on Enhanced Oil Recovery, Tulsa, OK, (April 17-20).
9. Potter, G. and D. Groves, "Displacements, Saturations, and Porosity Profiles from Steady-State Permeability Measurements", Paper SPE 19679 presented at the 64th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, San Antonio, TX, (Oct. 8-11, 1989).
10. Oak, M., "Three-Phase Relative Permeability of Water-Wet Berea", Paper SPE/DOE 20183 presented at the 1990 SPE/DOE Symposium on Enhanced Oil Recovery, Tulsa, OK, (April 22-25).
11. Oak, M., "Three-Phase Relative Permeability of Intermediate-Wet Berea Sandstone", Paper SPE 22599 presented at the 66th Annual Technical Conference and Exhibition of the Society of Petroleum Engineers, Dallas, TX, (Oct. 6-9, 1991).
12. Ebeltoft, E., J. Iversen, K. Vatne, J. Nordtvedt, and M. Andersen, "A Novel Experimental Apparatus for Determination of Three-Phase Relative Permeabilities at Reservoir Conditions", Paper SCA-9636 presented at the 1996 Int. Symp. Of the Society of Core Analysts, Montpellier, France, (Sept. 8-10).
13. Naylor, P. and D. Puckett, "In-Situ Saturation Distributions: The Key to Understanding Core Analysis", Paper SCA-9405 presented at the 1994 Int. Symp. Of the Society of Core Analysts, Stavanger, Norway, (Sept. 12-14).
14. Maloney, D. and K. Doggett, "2D X ray Scanner and Its Uses in Laboratory Reservoir Characterization Measurements", Presented at the Fourth International Reservoir Characterization Technical Conference, Houston, TX, (March 2-4, 1997), pp. 185-198.
15. Vinegar, H., "X ray CT and NMR Imaging of Rocks", *J. Pet. Tech.*, (March 1986), pp. 257-259.
16. Vinegar, H. and S. Wellington, "Tomographic Imaging of Three Phase Flow Experiments", *Rev Sci. Inst.*, (January 1987) **58**, 1, pp. 96-107.
17. Withjack, E., "Computed Tomography for Rock-Property Determination and Fluid-Flow Visualization", Soc. Pet. Eng. Paper 16951, 1987.
18. Coles, M., E. Muegge, and E. Sprunt, "Applications of CAT Scanning for Oil and Gas Production Research", *IEEE Trans. Nuc. Sci.*, (April 1991) **38**, 2, pp. 510-515.

TABLE 1. Comparison of Germanium Detector and Image Intensifier Results

Germanium Detector Measurements		
Brine thickness, cm	Intensity, counts/second	Brine thickness predicted from best fit, cm
0.00	13,476	0.00
0.49	6,781	0.49
1.02	3,270	1.01
1.51	1,624	1.51
Best fit linear equation:	Thickness, cm = -0.715(Natural log of Intensity) + 6.799, $R^2 = 1.00$	
Image Intensifier Gray Scale Measurements		
Brine thickness, cm	Gray Scale Value	Brine thickness predicted from best fit, cm

0.00	168	0.00
0.49	131	0.49
1.02	100	1.01
1.51	77	1.52
Best fit linear equation:	Thickness, cm = -1.938(Natural log of Gray Scale) + 9.936, R^2 = 1.00	

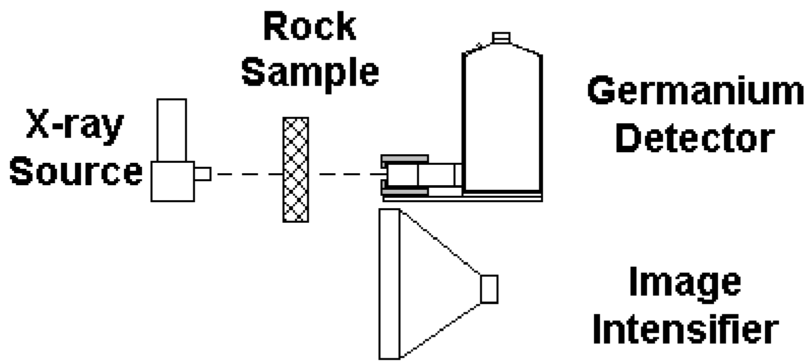

FIGURE 1. Scanner arrangement.

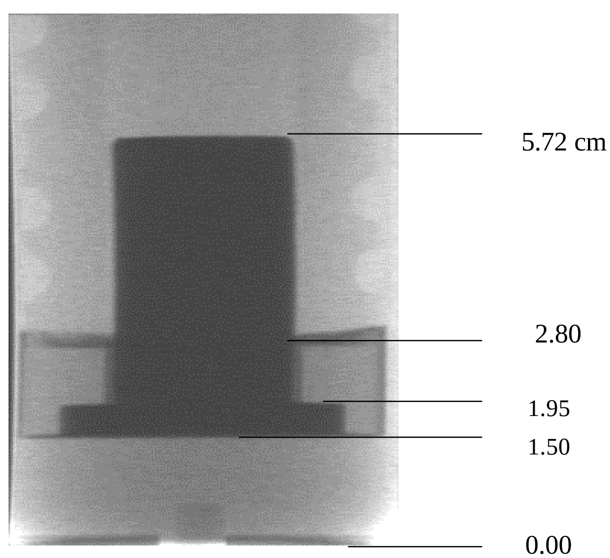

FIGURE 2. X-ray image of a chalk plug within a Teflon centrifuge tube.

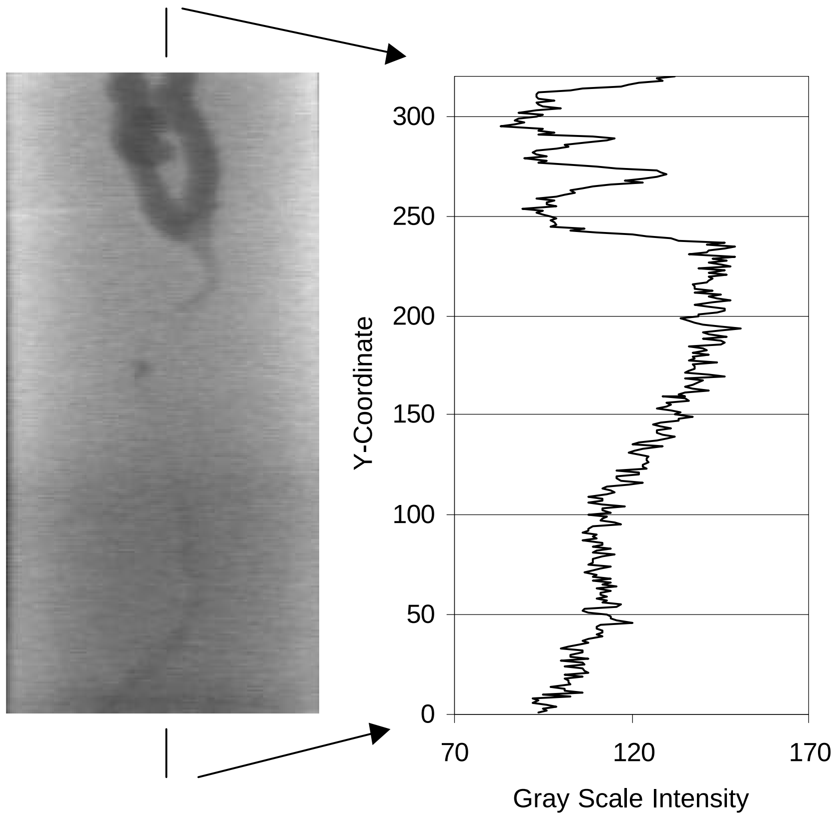

FIGURE 3. Image of the chalk plug of figure 2 showing internal features not evident from visual inspection. The graph to the right of the figure displays gray scale intensities along a vertical traverse through the center of the image.

FIGURE 4. X ray image of a slab of Bluejacket sandstone showing significant heterogeneity.