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X-RAY TOMOGRAPHY OF PRESERVED SAMPLES FROM THE GEYSERS SCIENTIFIC COREHOLE

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ABSTRACT

Approximately 800 ft. of continuous core was recovered from borehole SB-15 D (on unit 15, near the site of the abandoned Geysers Resort) during a recently completed drilling operation funded by the USDOE. Sections of this core were collected at 50 ft intervals for subsequent examination as drilling proceeded. Five foot sections were not removed at the drill site, but were sealed in the innermost sleeve of a triple tube coring system to minimize drying and disturbance of the core.

All cores remained sealed and were radiographed within 72 hours of drilling: the five foot core from near 1400 ft. was scanned within 18 hours of drilling. A third generation x-ray scanner, which uses high energy radiation to penetrate the aluminum sleeve and 3.5 inch cores, was used to make preliminary radiographs and to collect multiple views of the sample as the core is rotated in front of the beam. True three dimensional tomographs are then reconstructed from the data. At present, the images have a spatial resolution of approximately 140 micrometers and can resolve contrast differences of 0.2%. The tomographs clearly show differences in lithology with depth in the reservoir. Partially filled fractures, vein selvage and vuggy porosity are all evident in parts of the core.

A principle goal of the imaging effort is to help determine the fluid content of the reservoir. Important questions to investigate include water loss during core recovery, infiltration of drilling fluid, and the heterogeneous distribution of pore fluid. Images show that radial gradients in x-ray attenuation commonly occur in jacketed cores. Regions of excess attenuation extend about halfway into the 3.5 in. core, and are probably caused by mud invasion induced by capillarity of the small scale porosity of the graywacke matrix. X-ray measurements will be coordinated with other independent measurements of fluid content underway in separate studies, particularly NMR spectroscopy of frozen 'pressure core,' and compressional velocity and electrical resistivity measurements.

INTRODUCTION

The successful completion of The Geysers scientific corehole at the site of SB-15 (near the abandoned Geysers resort) provides an unprecedented opportunity to study rocks from the upper regions of The Geysers steam reservoir. High quality core was recovered starting near 800 ft extending to ~1600 ft depth from a sidetrack starting from the former production well, SB-15. The rock was characterized at the drill site by Hulen and Nielson as "highly fractured, heavily veined, but weakly altered Franciscan graywacke with minor argillite." The graywacke's origin appears to be turbiditic as indicated by the graded beds, load structures and the interbedded argillite, a dark organic-rich shale which exhibits flame structures into the graywacke. Details of the drilling operation and a first analysis of the rocks encountered are given by Hulen et al., 1994. Sections of this core were collected at 50 ft intervals for subsequent examination at Lawrence Livermore National Laboratory. At alternating intervals, either 1.5 ft of core was selected and sealed, or a 5 ft section was preserved. The five foot sections were not removed from the core tubes, but were sealed at the drill site with caps fitted with 'o' rings to minimize drying and disturbance of the core.

The jacketed cores are examined with a third generation x-ray scanner, which uses high energy radiation to penetrate the aluminum sleeve and three inch cores. Two types of data are collected: digital radiographs and tomographs. Radiographs are made by collecting two dimensional projections of x-ray transmission through the sample on high resolution film. Tomographs are produced by collecting multiple views of the sample as the core is rotated in front of the beam, and then reconstructing true three dimensional images using computational techniques. Both types of images are useful for locating highly fractured regions, for detecting structural features such as filled veins and folds and for detecting changes in lithology. Improved estimates of the amount of stored water at The Geysers are also of interest because these data are critical for predicting the performance and lifetime of the reservoir. Water content can in principle be determined by weighing recovered core as it dries under controlled conditions. However, water content estimates can be biased either by invasion of drilling mud or by fluid loss as the core cools and depressurizes on its way to the surface. High resolution x-ray methods have potential for evaluating the importance of these artifacts. Scoping tests of tomographic methods for small, unjacketed cores of graywacke from deep in the reservoir in the northeast Geysers (Bonner, Roberts and Schneberk, 1994) determined that pore fluid could be detected. However, changes in x-ray attenuation caused by saturation were comparable to fluctuations resulting from grain scale heterogeneity. Measured porosities for that graywacke, cored at ~8400 ft in NEGU-17, are ~1%, near the low end reported for the Geysers reservoir (Gunderson, 1990). Porosity is not yet known for the relatively shallow SB-15 rocks, but may well be higher than for the NEGU-17 samples. Therefore, changes in x-ray attenuation associated with pore fluids should be easier to detect than for the NEGU-17 core.

EXPERIMENTAL APPARATUS AND METHODS

The x-ray imaging system used here has several advantages as compared to systems typically used for studies of rocks, which are usually adaptations of medical systems. These include higher energy x-rays, better spatial and contrast resolution, and specialized reconstruction software. Both film radiography and CT were performed with a PHILLIPS 450 kVp source. Radiographs were taken with single m film with a source to film distance of 53 in. at an energy of 125 kVp. Imaging was performed with the PCAT scanner which uses a cone shaped beam of x-radiation to illuminate the object and a two dimensional detector to collect the transmitted radiation. This system includes a variable integration rate CCD camera, lens-coupled to a piece of scintillator glass. A 1024 by 1024 CCD chip with a dynamic range of 14 bits detects the output of the glass. A rotational stage spins the sample to obtain third generation (rotation-only) scans - a 2D radiograph is acquired at each rotational angle, and reconstructed directly into a 3D volume. To minimize the impact of source unsharpness the magnification was kept at 1.04 with a source to detector distance of 134 cm. This configuration results in a cone angle of 2.2 degrees requiring the use of the Feldkamp code for image reconstruction. The 10.16 cm field of view was employed for each of the scans which results in a pixel size of 97 micrometers and an effective spatial resolution of approximately 140 micrometers (as measured by the ASTM Full Width Half Maximum technique). Contrast sensitivity of this scanner was measured at 0.2% with aluminum penetrameters. The most extensive scans, which inspected 4 in. sections of core took 8 hrs to complete. All radiographic data were processed and reconstructed with software developed at LLNL. Additional discussion is given by Bonner, Roberts and Schneberk, 1994.

RESULTS AND DISCUSSION

Test of Core Sealing Method–A primary goal of the scientific coring project was to retrieve material with the in-situ water content as well preserved as possible (Hulen and Nielson, 1994). A triple tube coring system was used for the LLNL samples to maximize the possibility of recovering representative core from depth. Separate attempts to 'pressure core' while the hole was sealed and pressurized from the surface, which minimized the loss of steam during retrieval, were also made by Withjack and colleagues. The triple tube coring system had not previously been used in a geothermal field. Therefore, a test was devised to verify that the tube had been successfully sealed. Since the laboratory air in which the core was stored ranges in relative humidity from 20 to 30%, values lower than 100% inside the core tube would indicate that the atmosphere had exchanged with the ambient atmosphere subsequent to capping the tube at the drill site. First, a plastic tube was glued to the end cap of the core and a hole was drilled inside the tube through the end cap. A humidity sensor, which very nearly fills the plastic tube, was then inserted to sample the internal atmosphere for one week. The humidity increased rapidly at first and then steadily increased until it reached 100% after several days. Although only a single 1.5 ft core from 918.9 ft has been tested to date, and loss of fluid while the core barrel is on the wireline must be considered, the methods for sealing the tubes on site appear to be reliable.

Radiographs–Radiographs are taken as soon as possible of all received core to make a preliminary judgment of core quality and locate regions of interest for further study. Radiographs are x-ray shadowgraphs of an object, with denser regions producing less exposure on the film or detector collecting the image. Exposures of the entire core can be obtained rapidly, usually within a few minutes. Two examples of radiographs taken of 5 ft core from coring run 7, 875 ft and run 68, 1415 ft, are shown as Figure 1 a, b. Brighter regions absorb more of the illuminating radiation; numerals seen on the radiograph are lead markers placed outside the core tube before the exposure to locate points on the image as the source is moved relative to the core. These images have been filtered to enhance edges by locally increasing the contrast. The shallower core is less competent and more highly fractured than the core from 1415 ft. Linear features approximately normal to the core axis, such as those just above the 3 and midway between 6 and 5 in Figure 1a and near 3 in Figure 1b, are very likely drilling induced discing fractures. These images were produced by digitizing the film negative with an imaging system limited to eight bits of dynamic range in brightness, considerably less than the original. Drop outs in the core section may not necessarily be real, and are primarily an artifact of the imaging method.

Tomographs–An example of a high resolution tomograph is given in Figure 2. This is a radial cross section of the 875 ft core shown in the radiograph of Figure 1a, scanned between locations 4 and 5 and high pass filtered to enhance contrast. Brighter areas indicate higher x-ray attenuation. The narrow ring surrounding the core is the aluminum core tube. Bright linear sub- parallel features are partially mineralized veins which appear to be discontinuous at high resolution. Conspicuous gaps in the mineralization are characteristic at this depth, and seem to indicate vuggy porosity. Another feature, roughly perpendicular to the filled veins, appears to be a fracture crossing the core at a high angle.

Four radial sections are shown as Figure 3 to illustrate the range of structural features that can be resolved in the tomographs and to show the effect of depth in the reservoir. Figure 3b is of a relatively shallow core, taken at 918 ft. The missing material in the upper left may be associated with a large mineralized vein and will be examined in detail. A ring like region of higher attenuation extending inward from the outer boundary in all cores differs in detail in each case but is a common feature at all depths.

It appears that the gradient in x-ray attenuation can be related to invasion of the core by drilling mud. An enlargement of the radial tomograph taken of core from run 68, depth 1420 ft, Figure 4a, shows an invasion front similar to that seen to varying degree in the radial tomographs made at all depths. A region of excess attenuation beginning at the outer radius extends into the interior. The invasion front is not completely axisymmetric, but changes character in the northeast quadrant. This section of the core contains a contact between heterogeneous, coarser grained rock and fine grained material, possibly argillite. The mud invasion is less extensive in this area. It should be noted that beam hardening artifacts, which occur in tomographic reconstructions as a result of preferential radiation at lower energies, appear as radially symmetric rings starting at the outer edge of a sample. The asymmetry of the 'c like' feature coupled with the observation that the heterogeneous and fine grained sections have similar average density, e.g., x-ray attenuation, suggests that the beam hardening correction applied to all data is adequate.

The second part of the Figure, 4b, plots relative attenuation along the lines crossing Figure 4a. The first profile, labeled as s1, crosses the annular ring of high attenuation at both ends of the traverse. The second profile, s2, crosses the argillite and shows that attenuation is lower at this end of the traverse, consistent with less mud invasion in the region.

Radiographs of the deepest 5 ft core recovered for x-ray inspection, run 81, reveal a vuggy section near 1531 ft. The radial tomograph, Figure 5a, shows a slice through this structure, a complicated partially mineralized vein. Note also the fresh fracture near the bottom of the slice. Vertical slices through the central region of the core were examined to investigate the three dimensional character of the vuggy region. The vertical slices are ~0.7 in high, extending upward into the core from the radial slice. The slices are taken across the core progressing from the top to bottom of the radial section according to the index numbers shown next to the mineralized region. The slices show that this feature is not planar, but extends upward and to the left as a system of loosely connected stringers.

CONCLUSION

Images of sealed cores clearly resolve major structural features, changes in lithology, vuggy porosity, and other features with sufficient detail to draw conclusions about processes which have occurred in the reservoir. For example, cores from 820 ft contain intermittent veins suggesting that fluids undersaturated in the vein filling minerals have circulated through this region, dissolving material and leaving vuggy porosity. Tomography has sufficient spatial and contrast resolution to detect the prominent features of the lost circulation zone encountered in SB-15 D at 1396 ft. Features such as interconnected vugs in the metamorphic Franciscan vein, and large bladed calcite crystals, as described by Hulen et al., 1994, can probably be detected. None of the 5 ft cores sealed for x-ray inspection are close enough to the lost circulation zone at 1396 ft to sample it, but detailed inspections of the core from 1308 ft will be made to search for related features.

With further refinements, it may be possible to make quantitative measurements of mineralogy, porosity and water content and distribution. Preliminary measurements indicate that quantitative measurements of water content are possible if cores can be scanned as drying proceeds, but this depends on our ability to relocate points in the core in successive scans. It is also necessary to calibrate the effect of pore fluid on x-ray attenuation against measurements on fully saturated material, or independent measurements such as NMR, which is directly sensitive to hydrogen content. Another possibility for future work is to extract estimates of fluid diffusivity at reservoir conditions by searching for variations of mud invasion along the core. Sections at the top or beginning of a coring run are exposed to the drilling fluid for a longer time allowing for greater penetration. Alternatively, mud invasion may be useful for correlating changes of fluid diffusivity with depth or lithology. Chemical analysis of the mud and the outer sections of the core will be performed to determine if the attenuation contrast apparently caused by mud infiltration was enhanced by contamination by materials with high atomic number, that increase x-ray attenuation relative to pure water. It is also worth noting that areas near the core edges consistently show higher attenuation, opposite from the effect expected if fluid is lost during core recovery. However, it is possible that changes caused by fluid loss might be masked by mud infiltration. Time lapse tomography will prove useful for determining drying rates of recovered core, and the influence of fractures on imbibition and drying.

Studies of recovered core are indispensable for understanding The Geysers reservoir, but are inherently limited to sampling a small fraction of the reservoir volume. A principle long term goal of this x-ray scan fling program is to provide basic data for determining water content in-situ. Geophysical properties, such as seismic velocity and electrical conductivity, depend on water saturation. If the relationships between these quantities and water content can be calibrated reliably, borehole and field scale measurements of seismic and electrical properties could provide measures of water saturation in-situ at scales ranging to several kilometers.

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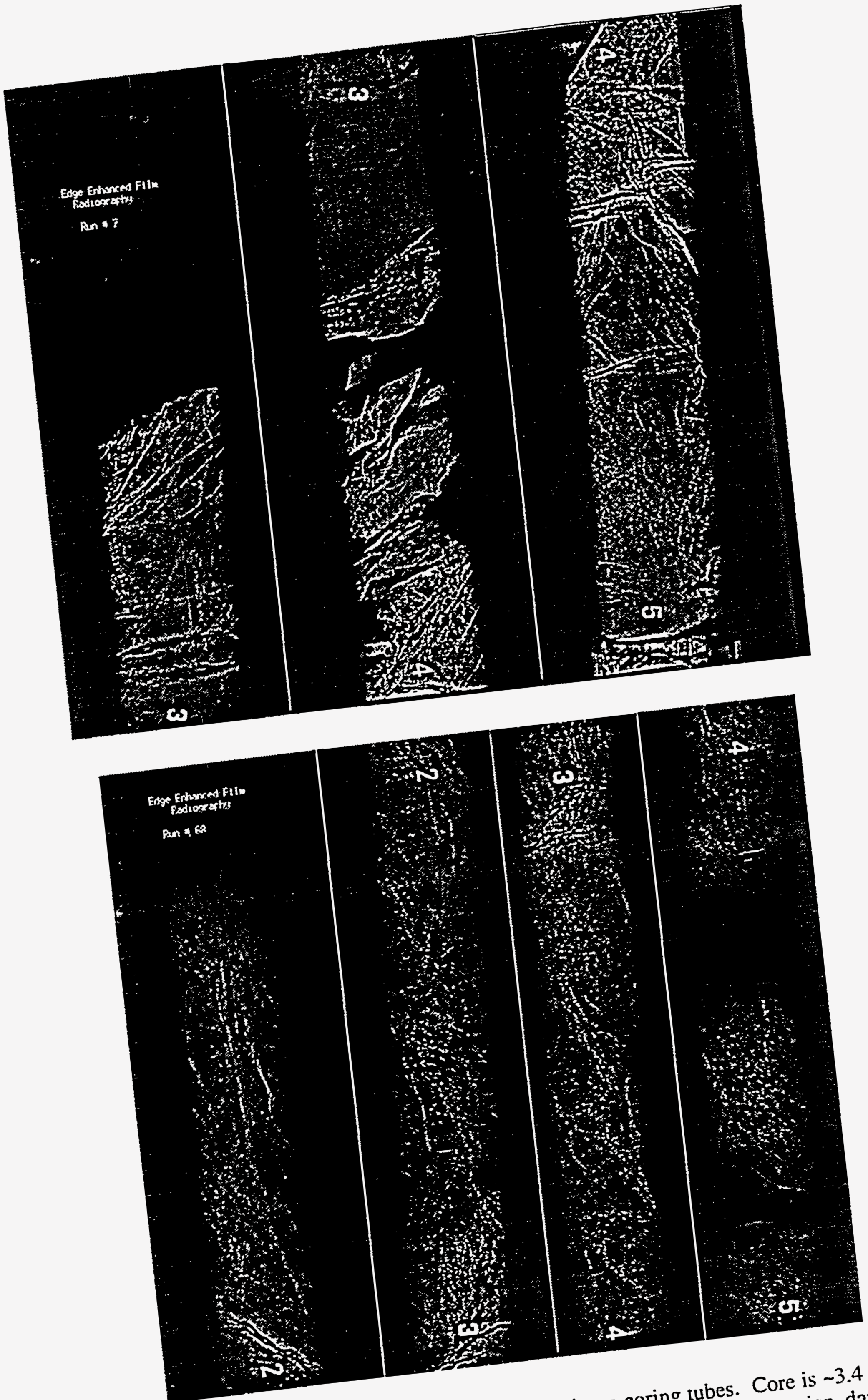

Fig. 1. Radiographs of five ft core lengths within sealed aluminum coring tubes. Core is ~3.4 inches in diameter. Images have been filtered to enhance edges. Brighter regions indicate higher x-ray attenuation, darker areas less x-ray attenuation. Numerals are lead markers placed on the outside of the cores for reference. a) Run 7, 875 ft depth. b) Run 68, 1415 ft depth.

Fig. 2. X-ray tomograph of run 7, 875 ft depth. This is a radial cross section taken between locations 4 and 5 (Fig. 1a). Pixel size is 97 μm, core is ~3.4 in. in diameter. The outer ring is the aluminum tube. Partially filled veins are readily visible.

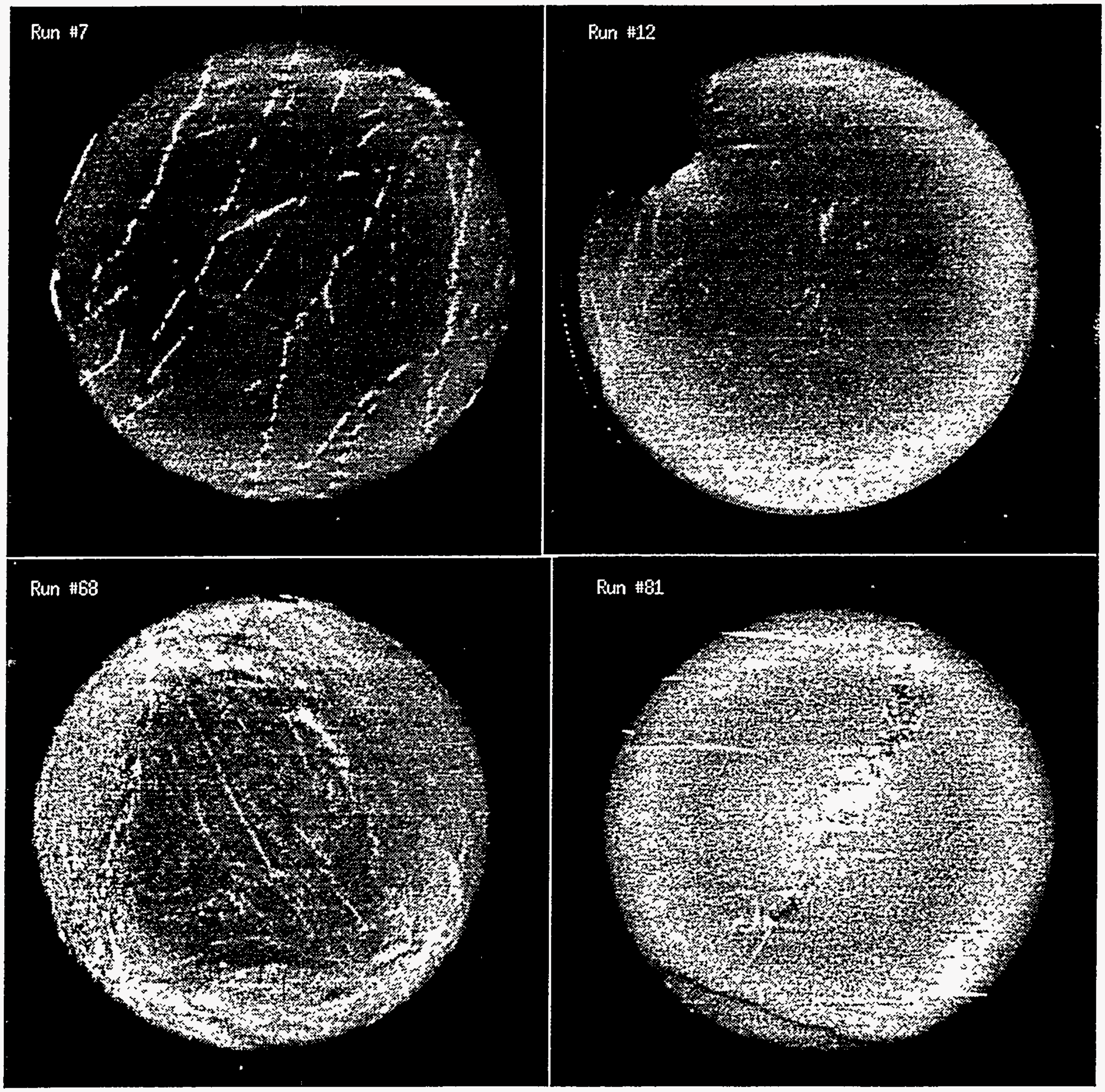

Fig. 3. Four radial tomographs taken at different depths to illustrate variability in texture, fracturing, and degree of mineralization. Core diameters are ~3.4 in. a) Run 7, 875 ft depth; b) run 12, 918 ft depth; c) run 68, 1420 ft depth; d) run 81, 1531 ft depth.

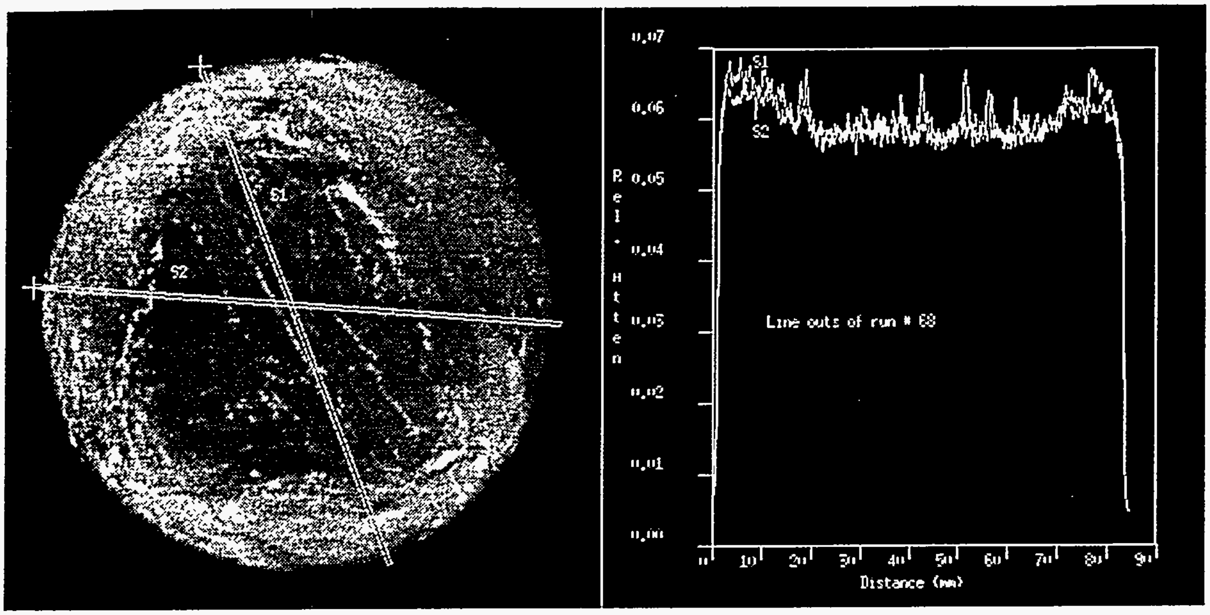

Fig. 4. a) Radial tomograph of run 68. 1420 ft depth, with enhanced contrast. Core is ~3.4 in. in diameter. Note the brighter (more highly attenuating) region around the perimeter of the sample. This is interpreted as evidence for mud infiltration during the drilling process. All the radial tomographs display this feature to some degree. In this sample the more highly attenuating region is not continuous, but is less pronounced in the northeast corner. The lines crossing the figure are plotted in b as relative attenuation versus distance. Both lines show higher attenuation near the edges of the core, however, S2 is less attenuating than S1 on the right hand edge, the area of decreased infiltration.

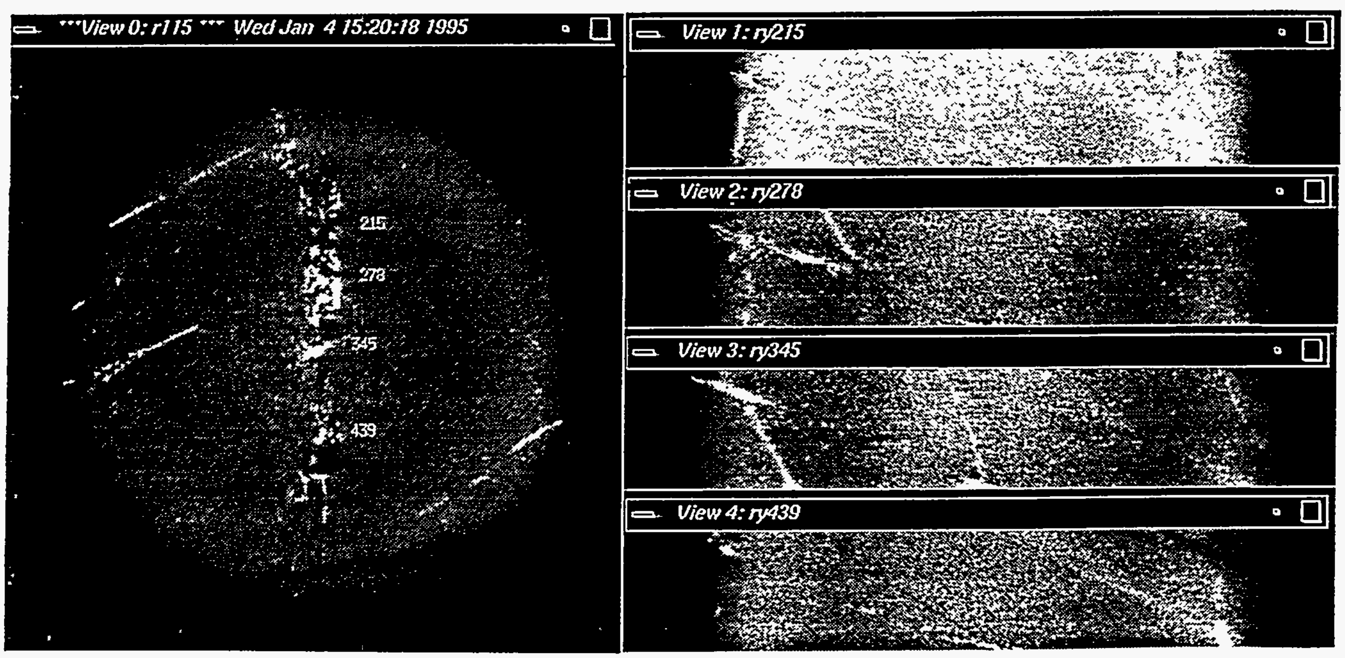

Fig. 5. Tomographs of run 81. 1531 ft depth. the deepest core examined using x-ray methods. a) Radial tomograph showing a partially mineralized vein. open fracture. and parallel filled fractures. Core diameter is ~3.4 in. The numerals indicate approximate locations where vertical tomographs have been reconstructed (b). Vertical slices are ~0.7 in. high.