CHARACTERIZATION AND SATURATION DETERMINATION OF GEOTHERMAL ROCK BY CT AND NMR

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ABSTRACT

This paper presents the results of special core studies to determine rock characteristics and brine saturations for the Geysers geothermal field, California. A coring procedure was developed to combine wireline retrieval with pressurized core recovery. Tritium in the coring fluid provided a means for detecting invasion. Nuclear magnetic resonance was applied as a new approach for saturation determination. Although reported water contents for some cases were below confidence levels, the NMR analyses offered relative comparisons and an alternative to uncertain Dean-Stark determinations. The tracer studies indicated that invasion increases with time when the core is detained downhole. The first core, detained for about 24 hours, had invasion levels (central core) in the range of 30% to 50%. The second core, recovered rapidly, appeared uninvaded with formation water saturations estimated to be low (3% to 13%). CT core flooding and modeling studies indicated vaporization and convection as the primary mechanism for coring-fluid invasion.

INTRODUCTION

The Geysers is one of the world's largest producing geothermal fields, with commercial development beginning back in the mid 1960's. Production from the field peaked in 1987, and since then deliverability has been declining at about 10% per year.[1] Other major locations for geothermal power include Indonesia, the Philippines, Italy, and Japan, with emerging interest in frontier areas such as Chile and Russia.[2]

The volume of water present in a geothermal system is a major factor in assessing a geothermal resource.[3] Conventional coring and analysis for water saturation (Dean Stark) may not be appropriate for geothermal rock because of reservoir properties (high temperatures and small porosities).[4] For example, downhole temperatures at the Geysers approach 400 °F and porosities are on the order of 1% to 5%. The coring procedure developed here is based on a modified wireline approach, and saturations determined using recently available NMR technology (Magnetic Resonance Core Analyzer).[5] CT-monitored displacement studies were conducted to investigate coring-fluid invasion mechanisms.

PROCEDURES

Core was brought to the surface under pressure and frozen on a dry-ice pack.[6] Two pressure core runs (10 ft long) were made: Run #69 and Run #88. **Table 1** lists the core runs, depths of the working segments, coring fluids, and the tests conducted. Plugs are identified within parenthesis. Core segments (8 to 12 in. long) were taken from the whole cores. Two segments (#1 and #3) from Runs #69 and #88 were shipped frozen for NMR analyses. Three disks were cut from each segment providing 2 plugs for NMR work, and 1 plug and 1 donut for tritium analysis. Cutting of the frozen core plugs was performed using liquid nitrogen as a cutting-tool coolant.

Core Run #69 was held down-hole for about 24 hrs while devising a method to retain pressure in the core barrel. Conventional pressure coring was proposed, but high down-hole temperatures exceeded equipment capabilities. Equipment and procedures were thus developed to obtain a pressure core with a conventional core barrel. A removable catch tube was fabricated above the lubricator to retain a retrieved core under pressure. The tube was fitted with connections to provide a pressurized air cushion in the well bore and to keep the surfaced core under pressure until frozen. The tritium tracer was metered into the mud line only during core Run #69.

CT CORE SCANNING

Scans of the NMR tested plugs (**Fig. 1**) provide a qualitative assessment of plug heterogeneity and density. Scanner resolution is approximately 0.5 mm (Delta Scan 150). All scans were taken at 120 kVp and 25 ma. In the CT images, the bright grays (higher x-ray attenuation) correspond to the denser regions. Around the periphery of the cores, there may be an apparent dense border which is actually an artifact of the scanning technique. Generally, the CT scans indicate that the core plugs are not homogeneous. The closely-spaced samples from each core segment, however, appear similar. For example, Samples 1N1 and 1N2 appear to be the most dense, while samples 3N1 and 3N2 appear to be the most heterogeneous. The CT densities qualitatively agree with the porosities from conventional analyses (**Table 2**).

Whole-core scanning was performed (**Fig. 2**) to study the feasibility of detecting fluid invasion. The CT scanner used here was optimized for saturation determination in conventional reservoir cores; the development of special tuning procedures was beyond the scope of this study. X-ray attenuation may occur when samples are scanned in open air giving the appearance of fluid invasion. Placing cores in a water bath or filtering the beam with aluminum reduces the effect.[7] The first and second columns show scans taken in air and in a water bath, respectively. The inserts show x-ray attenuation plots across a diameter. Before submerging, the cores were sealed in plastic film. The main difference in appearance between the left and right columns results from artifact reduction and a shift in overall x-ray attenuation.

The first pair of images are reference scans showing a clean, dry plug (CT1). The second pair shows a frozen whole core (pressure core Run #88, Segment #2) drilled without tritium. The third pair shows a frozen whole core (pressure core Run #69, Segment #2) drilled with tritium. The CT images indicate that the peripheral effect of x-ray beam attenuation makes it difficult to distinguish coring-fluid invasion from artifacts. Successful identification of mud invasion by CT has been reported by others when barium sulfate was used to increase mud density.[8, 9] Geothermal conditions, however, require use of a lighter, polymer-based drilling fluid.

SATURATION AND TRACER ANALYSIS

Dean-Stark extraction of a geothermal plug (graywacke, 1% to 5% porosity) typically yields a fluid sample one-to-two orders of magnitude smaller than that from a hydrocarbon reservoir. The Dean-Stark (DS Sw) and NMR (NMR Sw) saturations reported in **Table 2** lack strong correspondence due to errors in both the Dean-Stark and the NMR determinations. Before the field project was conducted, a feasibility study was performed to check the accuracy of the NMR saturations. [10] The analyses were performed in a uniform field using a 0.5 ms interecho spacing, and processed using an unconstrained bi-exponential model. The results indicated that NMR measurements were approximately +/- 20% PV (+/- 0.04 ml) of the water content determined by carefully controlled gravimetric measurements. Shorter interecho spacing was not available but would probably improve the accuracy of the results; the major component (T_2) typically had a decay time under 1 ms. This accuracy was determined as sufficient for testing the feasibility of the NMR approach, considering the error in saturation determination by Dean Stark may possibly be up to 2 times greater because of sample handling and small fluid volumes.

The water saturations for Core #69 are influenced by a 24-hour delay in bringing the core to the surface, and are several times greater than those for Core #88. The tritium tracer analyses also indicate significant invasion (Core #69). The outer donut samples (3T2 and 4T2) showed invasion levels in the range of about 50% to 70%. Generally, the samples from core Segment 1 show greater invasion than those from Segment 3. This is in qualitative agreement with the density indications from the CT scans. Corrections for drilling-fluid invasion are applied to the NMR Sw for plugs from Core #69 **(Table 2, Corr. Sw)**. A correction is applied to the NMR Sw for the plugs from each segment based on the average invasion of the plugs in that segment. The final saturations for Core #88 are not corrected for invasion since mechanistic studies (discussed below) indicate that the central part of this core is probably not invaded.

We note that the reported water contents for this core are below the confidence levels for both the Dean Stark and NMR analyses, but have merit for relative comparisons.

During shipment of water samples for tritium analysis several vials leaked (corrections to be made to the invasion calculations). Additional plugs were later taken from each core segment (Plugs 3A and 4A) for verification of invasion without sample loss. The results show qualitative consistency with plug sets from the respective segments.

CT FLOW STUDIES

CT experiments were conducted to improve our understanding of possible mechanisms that may account for invasion of coring fluid. We first assumed that the drilling fluid remained in a liquid state downhole; actual conditions are uncertain but there is a possibility of convective cooling. The core was first saturated with an untagged brine (2% sodium chloride). Next, tagged brine (sodium iodide) was injected at successively higher pressures. The advancement of tagged brine into the core was extremely slow; after 8 hrs. the advancement was about 1 cm at an injection pressure of 500 psi. In the field, drilling was performed at minimal overbalance conditions. The liquid injection test was halted as it appeared to be an inappropriate mechanism. The permeability of this core plug was estimated at roughly 0.0005 md.

Possible mechanisms for drilling fluid invasion include diffusion and vapor transport. Fick's Law analysis (**Fig. 3**) indicates that diffusion levels are 2 orders-of-magnitude too low to account for the measured invasion. The governing equation lends itself to an error-function solution that is available in many texts.[11] For our solution, the diffusion coefficient was taken as 2.0E-05, with other parameters in correspondence with the range of values in the figure. An approximate calculation using Darcy's law (**Fig. 4**) indicates that vapor convection may be a plausible mechanism.[12] The Darcy analysis used here assumed a core permeability as mentioned above, and a vapor viscosity of 0.02 cp. The results show that at 24 hours, for example, invasion depths are approximately in the range of the core depth penetrated (roughly 5 cm) at 10 psi over pressure.

A CT flow test was set-up to investigate vapor transport using xenon gas as an analog fluid. Use of CT and xenon gas offers the advantage of in-situ monitoring and fracture detection. The test was conducted with the downstream end of the core initially open to atmospheric pressure. Each row of 7 cross-sectional slices (**Fig. 5**) shows equally spaced scans along the core at a particular time. The first row (DRY1) shows the core in its initial clean condition. The second row (Xe1) shows invasion of xenon into the core after 30 min. of injection at 20 psi. Xenon is injected on the right side of the core and causes the shades to shift from a darker to lighter gray. The two slices on the extreme right show the highest concentrations, although traces of the gas can already be seen continuously along the core.

The next 2 rows (Xe2 and Xe3) show the gas distribution after increasing the pressure to 50 psi and holding for about 1 hr and 3 hrs, respectively. These images show increasing concentrations of xenon, particularly at the inlet (right) side of the core. Row Xe4 shows the xenon distribution after increasing the pressure to 100 psi; a linear feature (fracture) is apparent across the core (later confirmed visually). The final two rows depict conditions after 1 hr and 18 hrs of shut-in at 100 psi. The xenon injection test supports the mechanism of drilling fluid invasion by vapor transport, and suggests that vapor can be transported entirely through the core in a time frame consistent with drilling time.

CONCLUSIONS

1. A new approach is described for coring and analyzing geothermal rock for water saturation. Although reported water contents for some cases were below confidence levels, the NMR analyses have merit for relative comparisons and offer an alternative to possibly more uncertain Dean-Stark determinations.

2. Invasion levels increase with time when a core is detained downhole. One core, detained for about 24 hours, had average invasion levels in the range of 30% to 50%. A second core, recovered rapidly, appeared uninvaded and to contain low formation water saturations (3% to 13%).

3. The peripheral effect of x-ray beam attenuation did not permit the distinction of drilling-fluid invasion from scanning artifacts in CT scans of the whole core.

4. The results of CT coreflood studies (xenon injection) support the mechanism of drilling fluid invasion by vapor transport.

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TABLE 1 - SAMPLE IDENTIFICATION

RUN No.	SEG. No.	DEPTH RANGE ft.	FLUID/CORE USED	NMR TESTS	TRACER TESTS
61	-	1354.20 - 1355.10	Base/Conv.	-	CT Plug (CT1)
62	-	1368.10 - 1369.15	Base/Conv.	-	-
69	1	1422.70 - 1423.65	Tritium/Press.	2 Plugs (3N1,3N2)	Plug (3T1) + Donut (3T2)
69	2	1424.95 - 1426.60	Tritium/Press.	-	-
69	3	1423.65 - 1424.60	Tritium/Press.	2 Plugs (4N1,4N2)	Plug (4T1) + Donut (4T2)
69	4	1424.60 - 1424.95	Tritium/Press.	-	-
69	1	1422.70 - 1423.65	Tritium/Press.	-	Plug (3A)
69	3	1423.65 - 1424.60	Tritium/Press.	-	Plug (4A)
88	1	1600.60 - 1601.40	Base/Press.	2 Plugs (1N1,1N2)	Plug (1T1) + Donut (1T2)
88	2	1600.10 - 1600.60	Base/Press.	-	-
88	3	1595.30 - 1595.90	Base/Press.	2 Plugs (2N1,2N2)	Plug (2T1) + Donut (2T2)
88	4	1595.90 - 1597.00	Base/Press.	-	-

TABLE 2 - SUMMARY OF SATURATION ANALYSIS

RUN No.	SEG. No.	SAMPLE No.	He PV cc	POR. %	DS WATER ml	NMR WATER ml	DS Sw %	NMR Sw %	INVASION %	Corr. Sw* %
69	1	3N1	0.607	4.2	0.53	0.3008	87.3	49.6	40.0	24.8
69	1	3N2	0.686	5.1	0.54	0.2765	78.7	40.3	66.0	20.2
69	1	3T1	0.576	4.9	0.40	-	69.4	-	26.0	-
69	1	3T2	donut	-	10.00	-	-	-	67.0	-
69	3	4N1	0.496	3.4	0.45	0.1472	90.7	29.7	31.0	21.0
69	3	4N2	0.387	2.8	0.15	0.0458	38.8	11.8	20.0	8.3
69	3	4T1	0.695	3.1	0.21	-	30.2	-	20.0	-
69	3	4T2	donut	-	8.00	-	-	-	53.0	-
69	1	3A	-	-	0.80	-	-	-	68.0	-
69	3	4A	-	-	0.15	-	-	-	46.0	-
88	1	1N1	0.117	0.8	0.04	0.0154	34.2	13.2	NO TAG	13.2
88	1	1N2	0.070	0.5	0.05	0.0065	71.2	9.3	NO TAG	9.3
88	1	1T1	0.064	0.4	0.06	-	93.8	-	NO TAG	-
88	1	1T2	donut	-	1.80	-	-	-	NO TAG	-
88	3	2N1	0.352	2.4	0.05	0.0088	14.2	2.5	NO TAG	2.5
88	3	2N2	0.318	2.2	0.05	0.0116	15.7	3.6	NO TAG	3.6
88	3	2T1	0.252	1.2	0.15	-	59.5	-	NO TAG	-
88	3	2T2	donut	-	1.70	-	-	-	NO TAG	-

* Correction based on average invasion for plugs from respective segments.

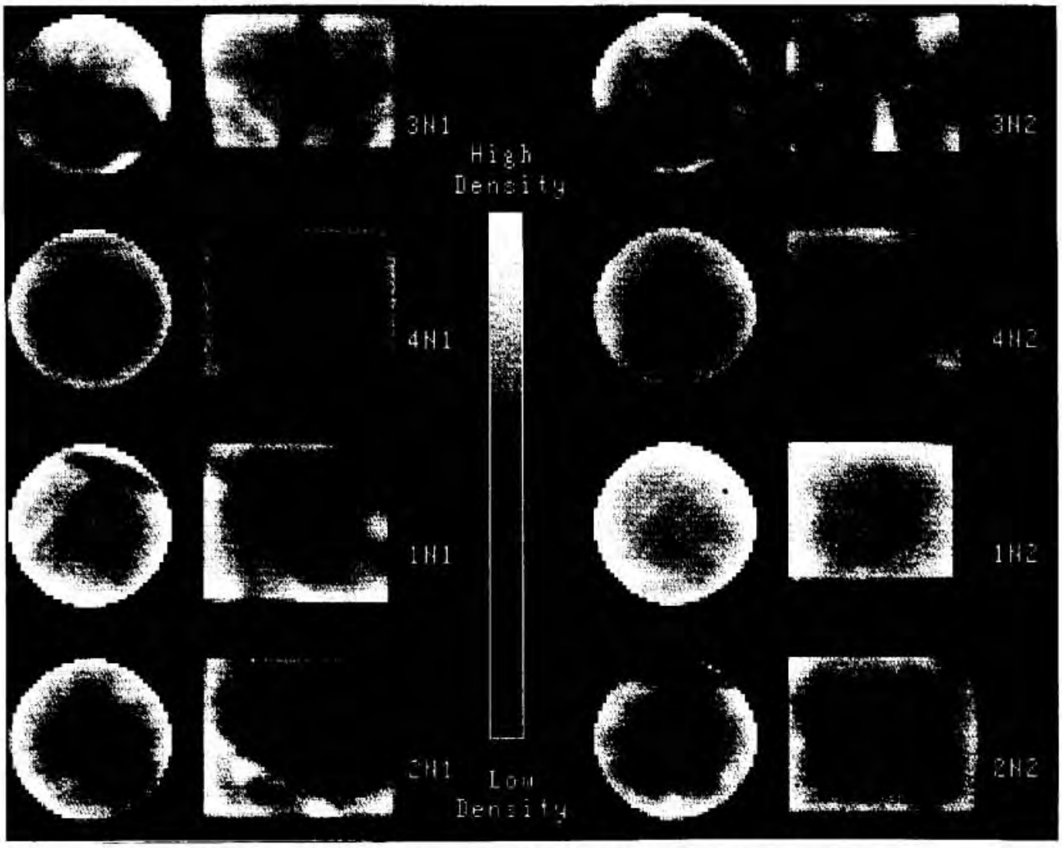


Fig. 1 - CT Scans of core plugs used for NMR water-saturation determination.

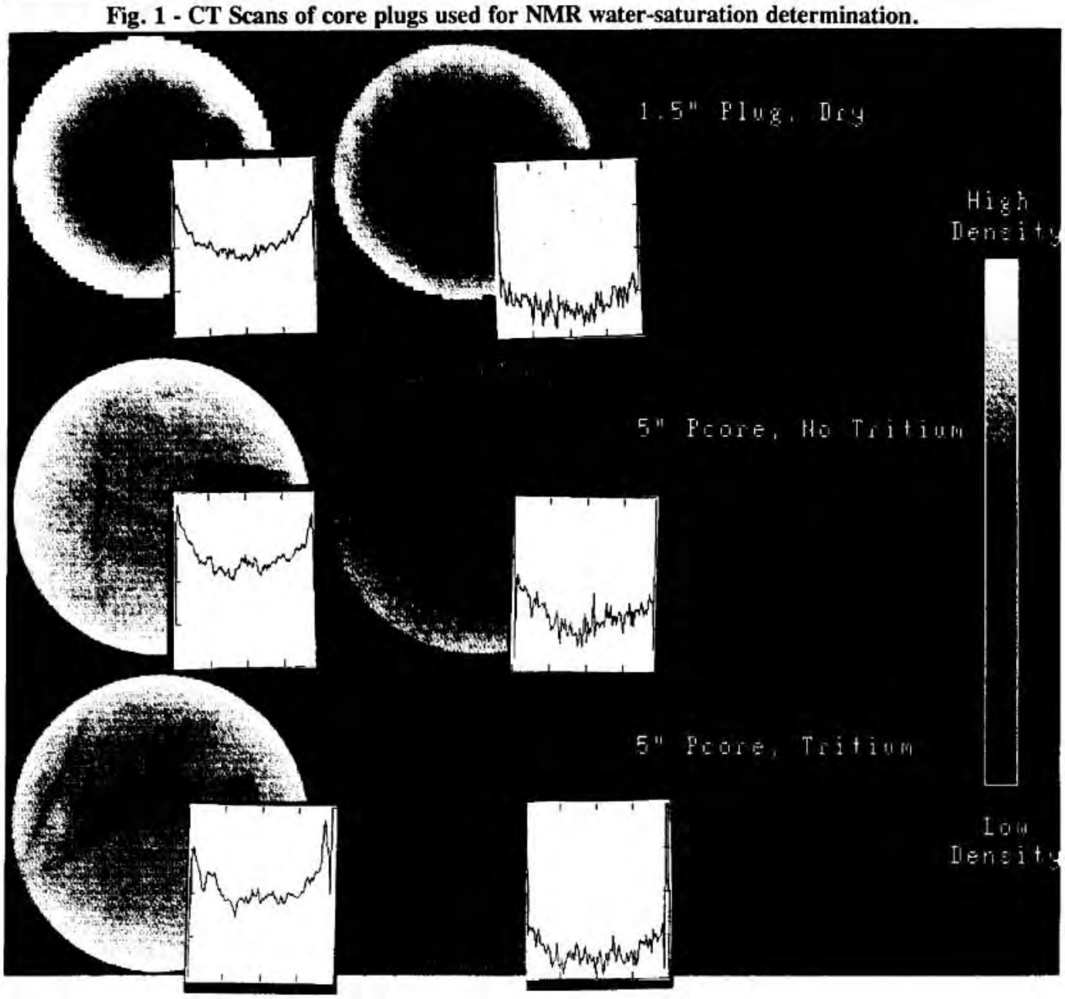


Fig. 2 - CT scans of core samples scanned in air (left) and under water (right).

Fig. 3 - Calculated Diffusion Concentrations

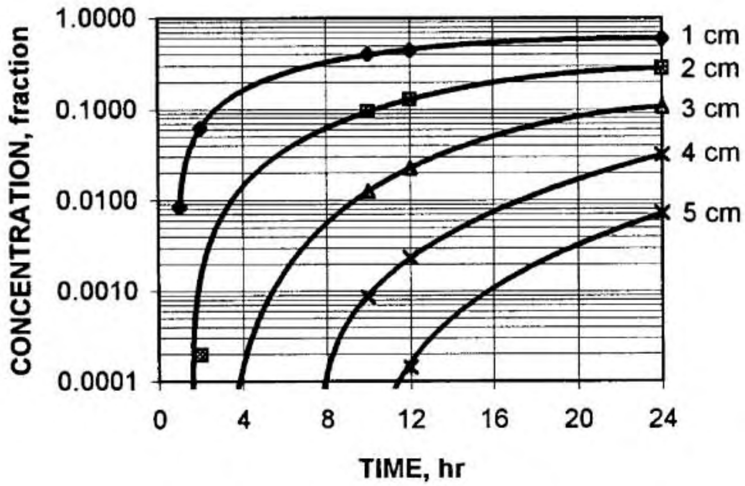
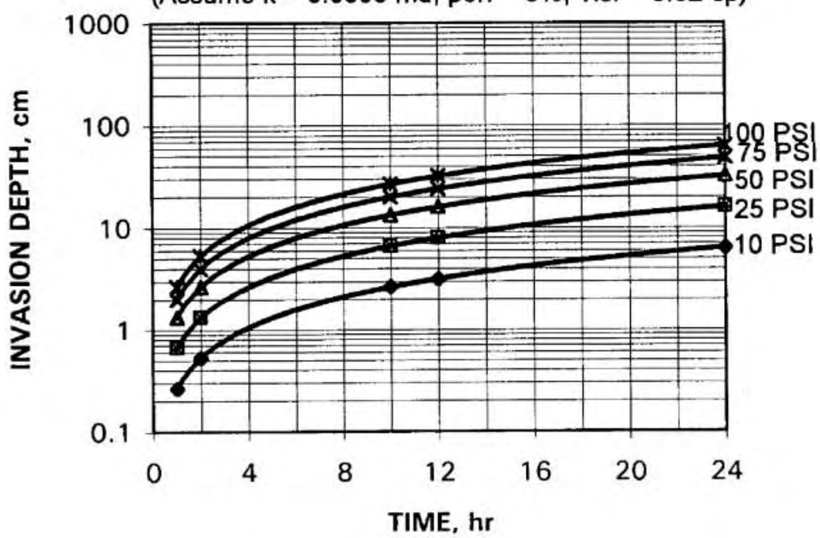


Fig. 4 - Calculated Invasion Depth by Vapor Convection

(Assume k = 0.0005 md, por. = 3%, vis. = 0.02 cp)



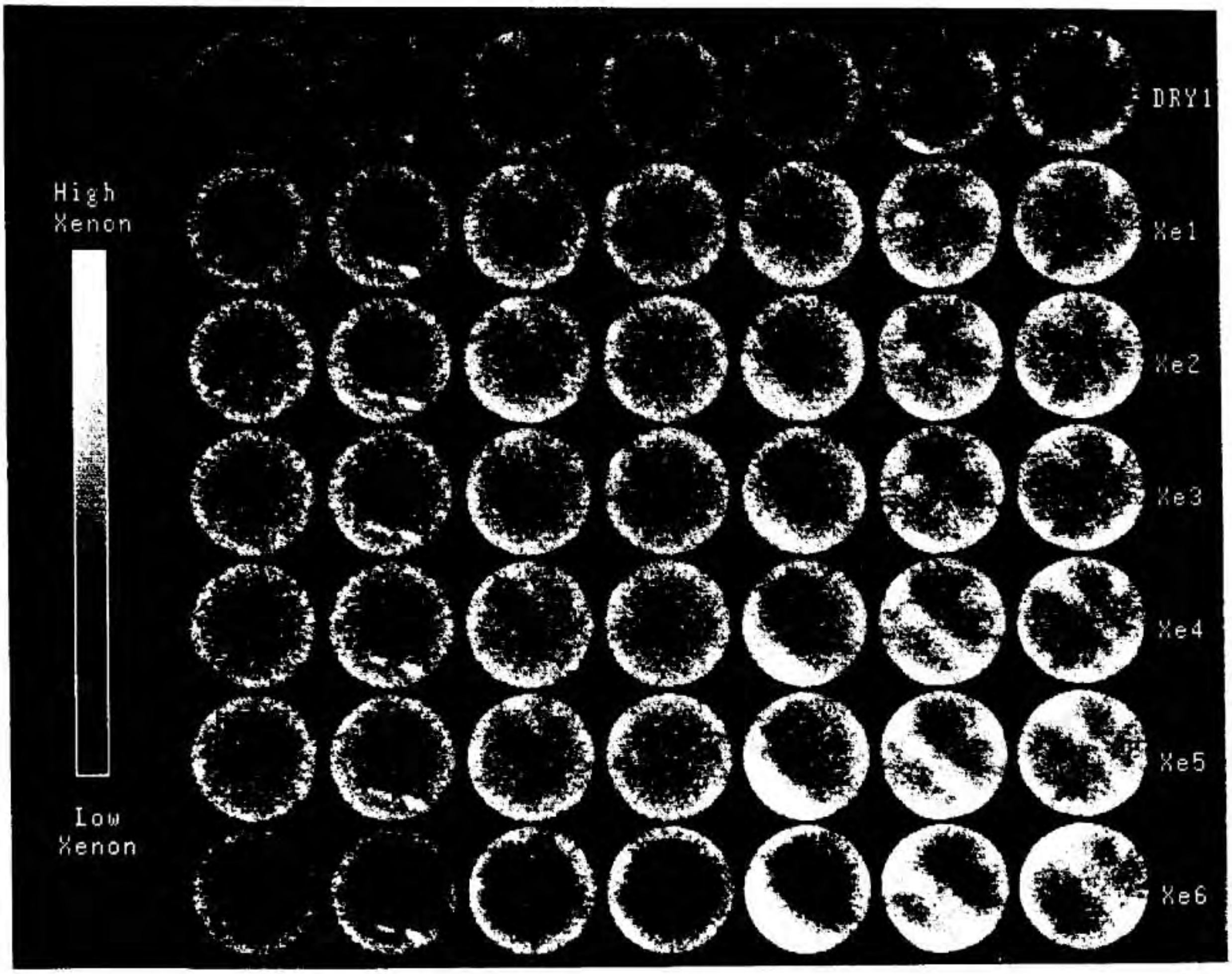


Fig. 5 - CT investigation of drilling fluid transport by vapor convection.