Infrared Thermography and Fracture Analysis of Preferential Flow in Chalk

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ABSTRACT

Preferential flow in fractured Cretaceous chalk has been investigated using infrared thermography (IRT) in a quarry in Denmark. Fracture mapping along the vertical quarry walls shows numerous horizontal fractures and four sets of vertical fractures respectively striking 25°, 60°, 145°, and 175°. Water flows out of the exposed walls mainly through fractures and to a minor extent by seepage through the matrix. To clarify which of the five fracture systems are hydraulically active, the exposure has been investigated using IRT. By making use of the contrast between the constant temperature of groundwater and the temperature of the exposed wall on a cold winter and a hot summer day, zones of groundwater discharge have been delineated. The results of the IRT suggest that the vertical shear fractures are the main hydraulically active conduits. Furthermore, the horizontal fractures are more hydraulically active in areas where they intersect a vertical stained fracture or in association with some flint layers. Stains of Fe²⁺ and Mn were observed primarily in fractures with a strike of approximately 25° and 175°, suggesting that the water flows preferentially in these fracture sets. The possible influence of the regional setting on the flow pattern is considered. The results suggest that the combined use of detailed fracture analysis and IRT is a valuable method for providing the input data required for both modeling and monitoring of fractured media.

The depositional, diagenetic, and tectonic history of chalk has created an unique dual-porosity reservoir rock with a high-porosity matrix, which is relatively impermeable \( \approx 8 \times 10^{-15} \text{ m}^2 \) (Frykman, 2001) given pore throats typically in the range 0.05 to 1.0 \( \mu \text{m} \) (Price et al., 1976). The chalk stands apart from all other limestones by virtue of its very fine grain size and relatively high friability (Selley, 1976) and can only function as an aquifer or a hydrocarbon reservoir because it is fractured. As opposed to the broader formation-type limestone, the hydraulic properties of chalk matrix vary little between sites. The origin of the basic fracture system is mainly tectonic, but a combination of factors such as dissolution, stress release as overburden is removed, and weathering can lead to significant enlargement of these initial fractures.

Fractures impose a dominating influence on the flow mechanisms in many chalk systems by offering preferential pathways for fluids. Chalk formations are of interest for engineering in the context of energy resources (petroleum, natural gas, geothermal water, and steam), water supply, and environmental problems (migration of chemical and radiation contamination, remediation, and protection). However, all fractures are not of equal importance for the flow regime, and they may furthermore exhibit a dynamic hydraulic activity (Commission on Geosciences, Environ. and Resour., 1996). Thus, identification of the most important hydraulically active fractures and hereby the preferred fluid pathways are crucial (Bloomfield, 1996).

The standard technique for understanding and predicting the preferential flow patterns in chalk includes the following steps: (i) identification of the sources or mechanisms that are capable of producing the stress field requisite for initiating and propagating the fractures, (ii) formulation of a fracture network model based on detailed quantitative descriptions of the geometry (orientation, trace length, spacing, and aperture) and the connectivity of different fracture sets in the fracture network based on geological mapping of outcrops and underground exposures and borehole data (Commission on Geosciences, Environ. and Resour., 1996), and (iii) investigation of the flow patterns using indirect methods such as pumping tests, well interference studies, and tracer tests (Downing et al., 1993; Price et al., 1993). The above indirect methods have the important limitation that they only provide aggregated information on the effects of the fractures at scales significantly larger than the fractures because of the data uncertainty on fracture locations, properties, connectivity, boundary conditions, fracture–matrix interactions, and host matrix properties. To obtain data that can provide more detailed insight into the flow mechanisms in fractured media, more refined techniques are needed.

In this respect, IRT is a promising technique that provides information on a refined spatial scale. Infrared thermography has been used in a variety of applications (Miljure, 1992) because it is a nondestructive, noncontact, and noninvasive technique that uses portable infra-red scanning equipment for detecting thermal changes in living organisms, objects, and domains. In relation to hydrology, the method has been used in a variety of ways, e.g., in connection with mapping of submarine groundwater discharge (Bayari and Kurttas, 2002; Portnoy et al., 1998), mapping surface temperature and circulation patterns in lakes (Anderson et al., 1995; Garrett and Hayes, 1997; Lathrop and Lillesand, 1987; LeDrew and Franklin, 1985), modeling heat dispersion in thermal effluent plumes (Davies et al., 1997; Jensen et al., 1988; Schott 1979), identifying subsurface springs (Roxburgh, 1985), examining spatial patterns of stream temperature (Torgersen et al., 2001), and studying moisture (water movement) in porous materials (Avdelidis et al., 2003). Applications of IRT have also been used to detect fractures/cracks and other deficiencies in materials (Moropoulos and Avdelidis, 2002; Shiratori et al., 1994). In other words, IRT has been used for detecting fractures...
and studying water flow and changes of water content in different media but has so far not been used for studying flow in fractured porous media.

The main objective of this study is to investigate how the combined use of detailed fracture analysis and IRT methods can be used for identifying hydraulically active fractures in chalk and hereby provide the input data required for the construction of conceptual fracture network models. This is done by analyzing the fracture network of the study site based on previous regional tectonic and hydrologic knowledge (presented in the Site characterization section) and site-specific investigations using scanline and borehole mapping techniques (presented in the Methods section). The results of the detailed fracture analysis are combined and compared with the results of IRT investigations. Through this study, it will be assessed whether and under which conditions the combined use of detailed fracture analysis and IRT field techniques are useful as a practical field tool in connection with studies of preferential flow in fractured chalk.

**MATERIALS AND METHODS**

**Site Characterization**

The study was performed at the Sigerslev chalk quarry, Denmark (Fig. 1). At the quarry, the uppermost 6 m are glacial till. Below the glacial deposits, 45 m of Cretaceous chalk are temporarily exposed in the quarry. The chalk is a fairly uniform carbonaceous mud with layers of nodular flint. The nodular flint outlines low mounds within the chalk (Surlyk, 1997; Surlyk and Håkansson, 1999). Pronounced horizontal fracturing as well as numerous vertical fractures occur within the chalk.

The chalk of the study area and region is deposited in the Danish Basin (Fig. 2). The Danish Basin is developed adjacent to the Fennoscandian Border Zone. The zone is delineated by large faults, which branch into the Danish Basin. During the Late Cretaceous and Early Cenozoic, dextral transpressional stresses induced partial inversion of the basin along the Fennoscandian Border Zone as well as dextral (right lateral) movement along the faults (Liboriussen et al., 1987). With a dextral strike-slip movement along the north–south faults, the maximum stress ($\sigma_1$) would be in northeast–southwest direction (Fig. 2). In this stress regime, a number of regional fracture systems might be expected: a system of extensional fractures parallel to the $\sigma_1$ direction, two systems of shear fractures with an approximate angle of $30^\circ$ from $\sigma_1$, and a system of stress release fractures perpendicular to $\sigma_1$ (Hobbs et al., 1976) (Fig. 2b). During the Neogene, a regional large-scale uplift occurred and 500 to 750 m of basinal deposits were eroded (Japsen, 1993; Japsen and Bidstrup, 1999), resulting in horizontal extensional fractures.

The water table elevation of the study area is dominated by the production of water (for the chalk treatment) from the two lakes in the quarry. The water table of the lakes was normally artificially kept at approximately 5 m below sea level (bsl),

![Fig. 1. Location map of the Sigerslev site with location of walls for infrared thermography (IRT) and wells for detailed IRT investigation. Additionally, a water table elevation map of the study area is presented.](image-url)
Fig. 1 (Aamand et al., 2001). During the study, the groundwater level was lowered to 20 m bsl, resembling the bottom of the quarry. However, this artificial lowering of the groundwater table only 400 m from the coastline did not result in any recordings of saltwater intrusion in a monitoring well situated between the coast and the active part of the quarry.

**Scanline Mapping of Site-Specific Fracture Systems**

Fracture data were collected along scanlines on the quarry walls and to some extent on the floor of the quarry (representing levels from +30 m to −20 m). The orientation, distance along the scanline, and length of the fracture traces were measured. The fracture surfaces were also described with special emphasis on Fe and Mn staining, which is an indirect indicator of current or past groundwater flow in the fracture. Hydraulic active fractures on the floor of the quarry were also registered.

**Borehole Investigation for Fracture Properties**

Two wells (Well I and II) with a diameter of 6 cm and a length of approximately 28 m (volume $\approx 0.08$ m$^3$) were drilled into the south-facing wall by the lake 2 to 3 m from the edge of the wall (Fig. 1). The wells were drilled with an azimuth of the well end on approximately N280 (parallel with the wall) and an inclination of 20° (from vertical) and without casing except for the upper 2 m. The well inclinations and the azimuth of well ends were chosen for the following reasons: (i) to allow for immersion of the televiewer image logging equipment; (ii) to penetrate the 20-m-thick bed sequence visualized on the wall; (iii) to measure variations in the water table of the wells, even at 20-m drawdown in the quarry; and (iv) to intersect a maximum amount of vertical fractures. To avoid direct cross flow between the wells, they were drilled with a separation distance at the surface of 10 m. When lowering the water table in the quarry to 20 m bsl, the level in the wells were approximately 10 m bsl.

Cores from the wells and televiewer image logs [borehole televiewer (BHTV)] (Zemanek et al., 1970) were used to map the flint layers and fractures in the two wells. The BHTV uses an ultrasonic beam with centerband frequency of 500 kHz to 1.5 MHz and a beam diameter of 0.5 to 1.0 cm. The BHTV operates by scanning the borehole wall at a rate of about three revolutions per second while the probe is steadily lowered in the borehole. The transducer is fired at a rapid rate and serves as both the source of the acoustic pulse and the receiver for the reflected signal. The BHTV image is oriented with respect to the local magnetic field by a down hole magnetometer. The image is split along the apparent north azimuth and “unwrapped” for display (Commission on Geosciences, Environ.
and Resour., 1996). With the image, it is possible to find the strike and dip of the fractures identified in the well. For Well II, an additional BHTV log was conducted approximately 1.5 yr after the detailed IRT investigation revealing accumulation of iron oxide along certain fractures.

Infrared Thermographic Investigations

Infrared thermography was used to map the groundwater outflow pattern in the quarry. By making use of the contrast between the constant temperature of the groundwater (≈8°C) and the temperature of the surface of walls, the groundwater discharge zones were delineated.

Infrared thermography investigations were performed with an AGEMA 550 camera. With the high-performance, handheld (horizontally), digital infrared camera, it is possible with the given calibration to measure temperature within the range of –20°C to +65°C with an accuracy of ±2°C and an automatic transmission correction based on distance, atmospheric temperature, and humidity. The camera was set up with an emissivity factor of 0.96, which represents the natural chalk surface. The spatial image resolution is 320 by 240 pixels, and the produced thermo grams (heat images) have up to 256 colors, which clearly show thermal profiles and range of temperatures. The wavelengths that IRT primarily image are in the short-wave region from 3 to 5 μm and the long-wave region from 7 to 14 μm. The camera used in this study operates in the spectral range 3.6 to 5.0 μm (AGEMA, 1997).

An IRT survey on the four walls in the quarry was performed during a cold winter morning (air temperature −14°C) to study the natural seepage from the walls with the aim of mapping large-scale preferential flow paths. The survey was conducted under calm weather conditions and before sunrise to avoid uneven heating of the walls due to the wind and the sun. Stored heat from the sun the previous day was neglectable since it was cloudy and cold weather.

Another IRT investigation, combined with a flow experiment (induced seepage), was conducted on a hot summer day when the weather conditions were calm, but the sun energy heated up the surface of the wall to approximately 25°C. The south-facing wall by the lake was chosen for this investigation, and Well I and II were drilled. This investigation, approximately 2.25 m3 of 13°C water was injected into Well I with rates of 20 l/min for 60 min and 32 l/min for 30 min over a total time period of approximately 1.5 h (referred to as Test 1). During the highest injection rate, Well I was filled with water. Simultaneously, thermal videotape and digital images were taken documenting the temperature changes on the wall. Water for the injection was supplied by a garden hose connected to the nearest water supply line. During the transport in the garden hose, the injection water was heated from approximately 8°C to 15°C because of the sun. The flow rate, which was measured by a flow meter installed at the end of the garden hose, was increased by 12 l/min after 1-h injection period because hardly any outflow on the wall was observed via the thermal videotape. Approximately 1.5 h after the injection into Well I, water was injected in Well II using an injection rate of 32 l/min over 70 min for a total amount of 2.25 m3 (referred to as Test 2). The starting time for Test 2 was determined on the basis of the thermal video showing re-establishment of the initial temperature pattern of the wall (±1°C) before Test 1 and the re-establishment of the water table in the Well I and II. Combined pressure and temperature transducers were installed in each well for monitoring changes in water table and temperature every 2 s (Fig. 3).

RESULTS

Results of the Fracture Analysis

In the quarry, one horizontal and four vertical fracture systems are recognized. The upper 9 m below the glacial till are crushed and heavily fractured by the Quaternary glaciers, which have overridden the region. The number of horizontal fractures increases rapidly upward in the upper 9 m of chalk. Below this upper glacially fractured zone, the spacing of the horizontal fractures is more uniform although it increases slightly with depth from approximately 20 cm at 20 m above sea level to approximately 40 cm at 20 m bsl. The horizontal fractures are usually more than 20 m long and pass through flint layers, which outline low mounds in the chalk. Along subhorizontal flint layers, horizontal fractures occur at the interface between flint and chalk. At the wall, water is primarily seeping out from the horizontal fractures at the intersection points with a vertical fracture or in association with some of the subhorizontal flint layers. At the intersections, channels are often eroded into the horizontal fracture plane, indicating a transport of sediment and hereby flow.

The orientations of the four vertical fracture systems are 25°, 60°, 145°, and 175° (Fig. 4a), which closely resemble the suggested fracture systems in the regional fracture model (Fig. 2b). The trace length of the vertical fractures varies from 20 cm to more than 20 m with an average of about 1.5 m.

The horizontal fractures divide the chalk into me-
The vertical fractures are categorized as multilayer, if they cross several mechanical layers, and single-layer fractures when confined to one mechanical layer. The orientations of the multilayer fractures mainly correspond to the 175° and the 25° fracture systems while the single-layer fractures mainly correspond to the 60° and the 145° fracture systems (Fig. 4b). Multilayer vertical fractures have a higher connectivity than single-layer fractures, and they are thus expected to have a larger effect on the groundwater flow.

Ferric iron and Mn staining on the fracture surface suggests that the fracture has been hydraulically active. The orientations of fractures with staining primarily correspond to the 25° and 175° fracture systems, and fractures with no staining correspond to the 60° and 145° fracture systems (Fig. 4c).

At the bottom of the quarry, hydraulically active fractures are recognized in shallow ponds and lakes because the water seeping out of the vertical fractures creates alignments of craters in the mud, which has settled in the ponds. The orientations of these hydraulically active vertical fractures correspond to the 25° fracture system (Fig. 4d).

By looking at the strike/dip of fractures observed in the image logs and cores from the two wells, both vertical and horizontal fractures were registered (see the Wulff nets, Fig. 5). Only one vertical fracture was observed in the lower part of Well I while Well II contained numerous vertical fractures. The information concerning the accumulation of iron oxide in fractures from the saturated part of Well II indicates that most of the vertical fractures are hydraulically active since dissolved Fe is transported with reduced groundwater and is oxidized and precipitates as it reaches the borehole. The largest accumulation of the iron oxide is, however, observed in the fractures with a north–south orientation corresponding to the 175° fracture system. Some of the horizontal fractures also have this iron oxide coating, especially the three fractures that are closely connected to the flint layer at level approximately −6.75, −16.5, and −23.75 m (Fig. 5).

The orientations of the four vertical fracture systems resemble the expected fracture systems suggested by the tectonic model with the maximum stress (σ1) pointing toward south–southwest. The 25° fracture system corresponds to the extensional fractures parallel to σ1, the 175° and 60° fracture systems correspond to the shear fractures, and the 145° fracture system corresponds to the stress release fractures. This implies that the extensional fractures (25°) and one of the shear fracture systems (175°) in combination are the main groundwater-controlling fracture systems. The 60° shear fracture system is less well developed than the 25° extensional fracture system, and the stress release fractures are more scattered and seem to play a minor role.

The finding that the dominant flow direction in the network of fractures is parallel with the coast is consistent with the observation that no saltwater intrusion was recorded in the monitoring well situated between the coast and the active part of the quarry where the groundwater table was lowered down to 20 m bsl.

**Results of the Infrared Thermographic Analysis**

**Natural Seepage**

By performing an IRT survey on four walls of the quarry representing two different levels, and

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**Fig. 4. Fracture analysis of vertical fractures.** (a) Rose diagram (showing orientation and frequency) of all vertical fractures measured in the Sigerslev Chalk Quarry. (b) Rose diagram of vertical fractures with estimated trace length, grouped into multilayer fractures and single-layer fractures. (c) Rose diagram of vertical fractures registered for staining, with staining, and without staining. (d) Diagram showing orientation of hydraulic active fractures in the bottom of the quarry.
Fig. 5. Image logs from Well I and Well II, indicating fractures, flint layer, and the water table in the two wells. The strike/dip of the fractures in the two wells are represented in Wulff nets.
B_{level:20to0m} (Fig. 1), on a cold winter morning (air temperature $-12^\circ$C), it was possible to construct a thermal map of the natural seepage of $\approx8^\circ$C groundwater from walls (Fig. 6). The thermal map shows that the south-facing walls are generally warmer than the east-facing walls. Additionally, the temperature generally increases with depth, and the hot spots are aligned horizontally on the south-facing wall.

Since the chalks matrix permeability is negligible, the main flow and associated heat conduction toward the walls must be transported along the active hydraulic fractures/pathways in the chalk. The fact that the south-facing walls are warmer than the east-facing walls is in agreement with the fracture analysis that suggested that the preferential flow pathways in the chalk trend northeast–southwesterly. In the unsaturated zone, these fracture systems will act as barriers for the capillary flow between the matrix blocks and hereby prevent groundwater flow and associated heat conduction toward the east-facing walls to the same degree as for the south-facing walls. The horizontal alignment of the hot spots is only seen on the south-facing wall and is more pronounced with depth. The increasing temperature with depth is a consequence of the gradient of the water table toward the wall, implying that the vertical drainage. These observations are in agreement with the location of the hot spots at approximately 10 m bsl and below on the wall adjacent to the lake (Fig. 5, Level B), which also corresponds to the level of the water table observed in the two wells established 2 to 3 m from the wall edge. Above 10 m bsl, the temperature of the wall adjacent to the lake is approximately the same at both faces and warmer than the air temperature of $-14^\circ$C. This is the domain of the capillary fringe, which can extend more than 30 m beyond the water table due to the pore-throat diameters in chalk (Price et al., 1993) and is affected by the $8^\circ$C warm groundwater. The same temperature pattern is seen at Level A (Fig. 5), but the level of the water table and the zone of the capillary fringe in the wall is unknown. The east-facing wall in Level A is also a bit colder in the upper part than on the south-facing wall. This seems to be a result of some protruding chalk parts on the east-facing wall, which have a larger surface area.

Flow-Induced Seepage

To further document the preferential flow pathways in relation to the mapped fracture systems, a detailed investigation was performed that included borehole information and IRT image series of the lower south-facing wall by the lake.

Relative changes of the water level in the wells were observed while water was injected with flow rates of 20 and/or 32 l/min into each well and observed in the opposite well (Fig. 3). Since the well setting, the fractures, and the lowering of the water table in the quarry do not warrant applications of analytical solutions for estimating hydraulic parameters from water level observations in wells (Duffield, 1996), we have only performed a qualitative assessment. By looking directly at the recovery data for the wells, both seem to recover relative quickly. For Well I, Fig. 3, the water seems to drain below the initial water table during recovery. This kind of rebound effect is normally only seen in high-
conductivity formations (Butler, 1998), which indicate that Well I is highly hydraulic active in the lower part. The temperature measurements in the wells showed that injection of 13°C water in Well I did not generate an increase in the water temperature in Well II. When starting the injection in Well II, the water temperature had decreased from 13 to 10°C in Well I, and the temperature continued decreasing to 9°C by the end of the investigation. Figure 3 also shows that 15°C water enters Well II in the beginning of Test 2. This is water that has stayed in the garden hose 1.5 h between the injection of water in Well I and Well II and thus has been subject to more heating by the sun. The thermal energy from the injection well was not noticed in the observation well, indicating that the two wells are not connected by hydraulically active fractures. These observations are corroborated by the hydraulic head observations and a tracer test (using NaSO₄) (Aamand et al., 2001), also indicating that the two wells are not in direct hydraulic contact. The thermal images from the wall illustrating areas where cold water (less than 16°C) is seeping onto the warm exposure at given times show a different outflow pattern from each of the wells to the surface of the wall (Fig. 7). The image series during injection in Well I show a very late and minimal breakthrough of the cold water at spots along some of the horizontal fractures. These cold spots seem to be located in the lower part of the wall and in the area where some of the vertical fractures were mapped on the wall surface. The cold spots seen at higher levels at a later time indicate a gradual saturation of the chalk. The wall surface is probably caused by draining of cold water from the bottom of the Well I as suggested by the recovery data of the water table for this well. The image series collected during injection in Well II shows an early and pronounced outflow on the wall surface at nearly all levels. The pronounced outflow from blocks of horizontal fractures in the upper part of the wall is due to the presence of fractures in the upper part near Well II that provide preferential conduits to the wall surface. The lint layer F3 seems to deliver a pronounced amount of cold water to the wall surface as suggested by the highly conductive horizontal fracture found in connection with F3 in Well II (Fig. 7). Since the time period between Test 1 and 2 is 1.5 h, injected water from Test 1 may contribute to the seepage in Test 2. Since the recovered water table in the wells are located approximately 10 m bsl, the majority of the fractures over 10 m bsl will be unsaturated before starting Test 2, but dead-end pockets in the chalk could be filled and thereby contribute in the seepage of Test 2. Given the information from the wells and the wall surface, the vertical shear fractures striking 175° seem to dominate the flow to the wall surface by acting as preferential pathways for water flow. Only a few of the horizontal fractures associated with flint layers seem hydraulically active.

**DISCUSSION AND CONCLUSIONS**

By identifying the sources or mechanisms that are capable of producing the stress field requisite for initiating and propagating the fractures in the study area, regional fracture systems were suggested, and their orientations were consistent with the obtained site-specific fracture information. Five regional fracture systems were identified. The fracture analysis based on fracture orientation, fracture trace length, staining on fracture surfaces, and hydraulic active fractures suggests preferential pathways in the chalk parallel to the coastline. The dominant pathway orientation was corroborated by the observation that no saltwater intrusion was recorded in the active part of the quarry. Since the identification of the most important hydraulic fractures and thereby the preferred fluid pathways is crucial for the development of a conceptual model (Bloomfield, 1996), IRT investigation was introduced to test the suggested preferential groundwater flow direction and the regional fracture model. The suggested preferential groundwater flow direction was confirmed by IRT where the actual outflow was mapped on the walls. With the nearly constant temperature of the groundwater and a temperature contrast between the ambient groundwater and the rock of approximately 8°C, it is possible to use IRT investigations to identify fluid pathways. This temperature contrast minimized the temperature errors introduced by factors such as sun energy, wind cooling, and a rough wall surface, which may generate an uneven heating of the wall surface. With the natural seepage wall survey, it was possible to observe and verify the suggested large-scale preferential flow paths. At a smaller scale, the induced seepage experiment combined with borehole information showed two different outflow patterns on the wall (Test 1 and 2), which again suggested that the vertical fractures dominate the flow regime. The investigation also underlined the importance of having the right position and orientation of the wells to get the maximum information concerning the dominating fractures of the flow regime and that there are certain limitations connected with interpretation of borehole data alone in fractured chalk. Individual borehole records cannot provide any information about the connectivity and trace length of the fractures. However, the accumulation of iron oxide in some fractures registered via BHTV in Well II seems to make it possible to outline the hydraulically active fractures in the well. The induced seepage experiment also suggests that indirect methods, such as the well interference test, cannot provide detailed information of the complex flow regime prevailing in fractured chalk. The weakness of the IRT method lies in the necessity of an exposure to the outflow and in the lack of information concerning the groundwater-flow distribution in the vertical fractures. Furthermore, the method requires that there is a pronounced temperature contrast between the flowing fluid and the rock media to delineate the flow paths. However, when these circumstances are present, an IRT investigation in combination with extensive fracture analysis seems to be a valid and useful tool for distinguishing between hydraulically active/inactive fractures and for outlining preferential flow paths in the fractured media.
Fig. 7. Thermographic image series illustrating the temperature changes with time of the south-facing wall by the lake in the quarry (Level B, Fig. 6) under injection of cold water in Well I (Test 1, upper image series) and Well II (Test 2, lower image series).
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