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GEOTHERMAL PROGRAMS AT LAWRENCE LIVERMORE NATIONAL LABORATORY

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Geothermal Programs at Lawrence Livermore National Laboratory

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ABSTRACT

Lawrence Livermore National Laboratory has a number of geothermal programs supported through two offices in the Department of Energy: the Office of Renewable Technologies, Geothermal Technologies Division, and the Office of Basic Energy Sciences, Division of Engineering, Mathematics and Geosciences. Within these programs, we are carrying out research in injection monitoring, optical instrumentation for geothermal wells, seismic imaging methods, geophysical and drilling investigations of young volcanic systems in California, and fundamental studies of the rock and mineral properties.

PROJECTS SUPPORTED BY GEOTHERMAL TECHNOLOGY DIVISION

The Office of Renewable Technologies, Geothermal Technologies Division, supports programs aimed at studying the migration of reinjected fluids, at developing methods for producing seimic images of volcanic terranes, and at developing technologies needed for measurements in geothermal fields.

Geothermal Injection Monitoring Project
(P. Kasameyer, T. Hauk, and S. Jarpe)

Reinjection of geothermal fluids is important for the successful operation a geothermal field for many reasons. Reinjection has significant effects, both beneficial and detrimental, on the performance of a geothermal field, and there are significant uncertainties about predicting these effects in realistic situations. For these reasons, the Brine Injection Technology Effort of DOE has set a high priority on the development of techniques to track injected fluid and to predict the impacts of injection on the geothermal field.

Fluid injection produces a number of distinct regions bounded by fronts which move through the reservoir as injection proceeds. Reservoir engineers model the evolution of these fronts in order to predict the performance of the geothermal field. More knowledge of the front locations away from observation wells would increase our ability to predict the front evolution.

Fronts change the physical properties of the reservoir medium as they pass. For example, in a porous reservoir, differences in salinity of the natural and injected fluids produces a change in electrical resistivity at the fluid front. Thus, geophysical methods, which measure the physical properties of inaccessible portions of the Earth, can be used to provide information about the location of fronts away from observation and sampling wells. Lawrence Livermore National Laboratory (LLNL) is studying the application of geophysical methods to provide information to reservoir modelers about the migration of injected fluid and the fronts produced by it.

Geophysical methods may do this well. They allow the interrogation of large volumes of the reservoir from the ground surface or from a limited number of boreholes. Different geophysical methods are sensitive to different physical properties, so they can locate different fronts. Many of the useful techniques are routinely used for a number of other purposes, so measurement, analysis and interpretation methods are being developed by a number of researchers. Because of these advantages, geophysical methods can inexpensively supplement point sampling methods as the means to provide data for prediction of reservoir performance.

Geophysical methods have two limitations that must be dealt with when they are used to monitor injected fluid migration. The first is that the physical response of the reservoir depends on many factors that change greatly from site to site, such as the porosity distribution, nature of the fractures, salinity of the fluids, resistivity of the rock matrix, and state of stress. As a result, the relationship between the passage of a front and the response of a particular geophysical method is strongly site specific. Second, geophysical methods have limited spatial resolution due to two factors, inherent non-uniqueness and geologic variability. When geophysical methods are used to monitor injected fluid, the problems associated with geological variability can be reduced by comparing measurements made before and after injection starts, or repeating measurements after the fronts have moved some distance. These limitations can be taken into account when planning a geophysical study.

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This project began with an anaylsis of the needs for geophysical monitoring methods, an assessment of the present state of measurement capability, and the development of a plan for increasing that capability (Younker, 1981, Younker, et al., 1983). In that analysis, it was found that we could identify methods that will work, that is, that met four criteria:

1. The changes in physical properties associated with different regions about the injection well can be calculated with some confidence.

2. The geophysical anomaly that would be observed in a surface or borehole survey can be calculated, in order to decide whether or not to use the method.

3. The experiments can be carried out on a routine basis.

4. The techniques are available to interpret the survey to infer the distribution of physical properties.

A number of methods meet these criteria and have been successfully applied to learn about the behavior of reservoirs. Examples include surface DC resistivity, applied at Cerro Prieto by Wilt and Goldstein, 1984, and surface gravity studies, used by Isherwood, 1977, to study changes at the Geysers geothermal field. These tools are available for use at geothermal fields, either as surface surveys or downhole measurement methods. Our objective is to increase the number and quality of geophysical tools available for monitoring injection. In order to accomplish this goal, we must deal with three questions:

1. Can new modeling techniques be developed for the assessment and interpretation of geophysical methods to be used to monitor injection?

2. Can new techniques, or innovative variations on old techniques, be developed to carry out measurements in geothermal areas?

3. Can we improve on our ability to predict the circumstances under which certain geophysical anomalies will be observed?

Our early efforts concentrated on the first two questions. An interpretation method was developed to use observed pressure fluctuations in a single well to determine average fracture orientations over distances of several hundred meters (Hanson, 1984). Cross-borehole EM tomographic methods and AC conductivity studies were evaluated in a number of environments, including two geothermal wells separated by 125 meters (Younker, et al., 1982). A high resolution micro-seismicity network was fielded in a typically noisy geothermal environment (Smith and Kasameyer, 1985). These experiments were aimed at developing new fielding and modeling methods.

Recognizing that the first two questions have applications in many areas in addition to reinjection, and that many people are working on providing answers to them, we are now concentrating on the third question. Our approach is to chose geophysical anomalies commonly observed at geothermal fields but whose origins are unknown, and to gather case history information documenting the circumstances under which they appear.

Two physical phenomena are being studied, microseismicity and electrical self-potential. Earthquakes are a well-documented phenomenon associated with the injection of fluids . In at least one case, the occurence of seismicity was shown to map at the zone where pressure exceeded a certain threshold (Hseih and Bredehoeft, 1981). In some geothermal fields, such as Raft River, no seismicity is seen, and in others, such as the Geysers, there is an association of the seismicity with production (Bufe, et al., 1981). While it is clear that detected seismicity could provide valuable information about the reservoir response to injection, more well-documented case histories are needed before we can predict when these signals will occur.

The movement of fluid or heat through a porous medium, or large chemical concentration gradients can produce electrical potentials which are remotely observable. Steady electric potential (SP) anomalies of several hundred millivolts have been observed above many geothermal fields, and it is expected that the induced fluid flow and thermal and chemical concentration resulting from injection and production will also produce SP signals. As is the case with seismicity, it is clear that repeated SP surveys may provide valuable information about the movement of fronts in the geothermal field, but more case studies are needed to provide the basis for being able to predict when they will occur.

Our SP and microseismicity studies are taking place at the binary power plant at Casa Diablo Hot Springs, near Mammoth Lakes, California, with cooperation from the Ben Holt Company.

A six channel, digital, event-detecting seismic monitoring system has been operating since 1984. The one kilometer wide, four station array is centered in near the injection wells. Three components are recorded at the central location, and vertical components of motion are recorded at the other stations. The array is capable of detecting magnitude –0.5 events near the injection zone, and provides the data needed to estimate the distance to the event. The three component station allows us to determine approximate locations for simple events. In FY86, we maintained the network and processed data as it was received. The rate and nature of local seismic events are being tabulated, and will be compared to changes in the operations of the injection system, and to natural tectonic events. A summary of the seismicity detected before and during the first year of operation is being compiled and will be sent to the operator for review before it is released.

In addition, approximately 75 SP stations were occupied in 1984, before operations began. This survey extended approximately 600 meters from the injection wells in six nearly radial lines. Three independent observations were made at each station to provide a test of self-consistency, and to detect areas with anomalously high local gradient. The stations were re-occupied over a year later, after several months of injection, and changes in the field were detected. These data are presently being analyzed to determine if these changes can be related to fluid motions induced by injection.

In the future, we will complete the analysis of the microseismicity data and SP data collected at the Casa Diablo Hot Springs, and continue to collect case history information by participating in an integrated field test at a site where injection is taking place.

Seismic Imaging in Volcanic and Caldera Systems
(J. Zucca and G. Zandt)

We are developing and testing innovative seismic imaging methods to be used to locate and characterize magma-hydrothermal systems in volcanic terranes where traditional seismic reflection surveys are often impaired by poor coupling and highly variable surface geology (Mooney and Brocher, 1987). Several experiments have been carried out:

1) In cooperation with the USGS, we produced seismic velocity and attenuation images of the upper 5 km beneath Medicine Lake Caldera, in northern California. These images were based on data from 8 explosions recorded 140 seismographs. A four square-kilometer area at depths of 3 to 5 km was identified in both images as a possible magma chamber. This project is described in papers by Evans and by Zucca in this volume.

2) We are taking advantage of the high quality seismic data set and well-known geologic structure at Medicine Lake to develop and test other innovative seismic methods for understanding geothermal reservoirs in caldera environments. Under contract to LLNL, Dr. Jose Rial, of the University of North Carolina, is using the three-component data from the Glass Mountain area to look for off-azimuth scattering from shallow crustal objects. George Zandt, of LLNL, is also evaluating the effectiveness of the receiver function methods to determine S-wave velocity structure beneath this array.

3) We attempted to produce a two-dimensional seismic tomograph through Obsidian Dome, in the Inyo chain in Northern California, using a commercial seismic crew for one day. This effort was not successful as we could not get seismic energy into the dome.

Geothermal Technology Development
(S. M. Angel and P. Kasameyer)

We are involved in two projects whose purpose is to develop and test innovative technologies that may be useful in locating and characterizing geothermal reservoirs.

1) Development of a high-temperature fiber-optics system for chemical and physical measurements in geothermal wells. Under the direction of S. Michael Angel, we are developing and testing a fiber optics system for making chemical and physical measurements under adverse conditions. Fiber optics sensors can eliminate the need for downhole electronics, connectors, elastomers and insulators, all of which tend to fail at temperatures in geothermal wells. We are developing and calibrating doped porous ceramic optrodes whose adsorption and emission spectra are sensitive to temperature and pH, and plan to develop and test additional sensors for concentration of other chemical species. In addition, we have begun experiments linking these optrodes to stainless steel encapsulated fiber-optic cables. With DOE funding, we are working with Dr. Shiv Sharma of the University of Hawaii, to begin testing this system in a geothermal well. This work is reported in this volume in a paper by Dr. Angel.

2) Cryogenic Gravimetry. We are assisting Dr. John Goodkind of University of California, in the deployment and analysis of data from two cryogenic gravimeters to be deployed at Kilauea, Hawaii. The purpose of this experiment is to record changes in the gravity field caused by the sub-surface movement of mass.

PROJECTS SUPPORTED BY THE OFFICE OF BASIC ENERGY SCIENCES

Continental Scientific Drilling Program: Thermal Regimes.

Salton Sea Shallow Thermal Gradient Project
(L. W. Younker, P. W. Kasameyer, and R. L. Newmark)

During November and December, 1985, the Lawrence Livermore National Laboratory and Sandia National Laboratories cooperated in drilling a series of shallow (80 m or 250 ft) holes in the southern Salton Sea as part of the Thermal Regimes Shallow Drilling Initiative. The intent was to complete the surficial coverage of the thermal anomaly offshore in the region north of the line of volcanoes. Temperature profiles in these holes were logged periodically up to 5 months after drilling to establish equilibrium temperatures.

These data allow us to close the thermal contours around the thermal anomaly, revealing its shape and extent. The contour map of the thermal gradients shows the thermal anomaly to be of arcuate shape, about 4 km wide and about 12 km long (Newmark, et. al., 1986), in contrast to earlier predictions of a circular shape. It extends only a short distance offshore, primarily in the northern and southern edges of the field. There is an asymmetry of the high thermal gradient zone relative to the chain of volcanic buttes, indicating that they may not mark the center of the resource.

These studies provide valuable constraints on the size and shape of the thermal anomaly at the Salton Sea. These constraints will be used to improve models of the hydrothermal system which produces the geothermal resource (Kasameyer, et al., 1984), and may lead to a better understanding of the relationship between large-scale plate motions and the local active magma-hydrothermal system.

Inyo Domes Research Drilling Project
(L. W. Younker, and colleagues from Sandia National Laboratory)

The purpose of drilling at Inyo Domes near Long Valley, California, is to understand the behavior of silicic magma as it intrudes the upper crust. This behavior, which involves the response of magma to decompression and cooling is closely related to both eruptive phenomena and the establishment of hydrothermal circulation.

A new phase of drilling into the Inyo Domes volcanic chain began in Long Valley in early June 1987. A hole is being continuously cored along a steeply dipping trajectory across the trend of the chain from a site near Inyo Craters reaching a final depth of approximately 1000 M. The hole will pass beneath the largest of the phreatic craters in a region of extensive faulting and fracturing. The hole is the fourth in a series of research holes that have explored both the extrusive and intrusive Inyo system.

The previous three holes, drilled outside Long Valley caldera, penetrated the largest of the Inyo lava domes and probed the parent intrusion within Sierran basement. The results have demonstrated the close relationship between eruption and shallow dike emplacement for silicic magma, delineated chemically tagged flow paths in the extensive/intrusive system (Vogel, et al., 1987), documented the excavation of a vent funnel prior to extrusion, and demonstrated the contrasting crystallization behavior of extruded and shallowly intruded magma. One of the conclusions reached in interpretation of these results is that silicic magma ascends as permeable foam and that the extent of degassing and hence eruptive behavior depends strongly on the permeability of the intruded environment. Observations in the latest hole will test these ideas by describing the behavior of the same magma in the more permeable caldera-fill environment, where both more rapid degassing and cooling are expected to have occurred.

SSSDP: Constraints from Borehole Gravity on Geothermal System Models for the Salton Sea Geothermal Field
(J. R. Hearst, P. W. Kasameyer, and L. W. Younker)

The purpose of this project is to use observations with a borehole gravimeter to learn about the density structure in the vicinity of the SSSDP well, and to use that knowledge to understand more about the evolution of the hydrothermal system at the Salton Sea. Since density is the most sensitive parameter indicating the degree of metamorphism within geothermal field in the Salton Trough, and the SSSDP hole was sited near the edge of the geothermal field, it was thought that extending the range of investigation about the borehole might detect the lateral border of the metamorphosed zone, if it lies within several hundred meters of the borehole.

Measurements were collected over the depth range of 3400 to 5700 feet within the SSSDP hole (Paillet, 1986). In addition, the vertical gradient of gravity above the hole was measured by carrying a gravimeter up to the top of the drilling rig. The observations can be summarized as follows:

1). The gravimetric density is within 0.02 gm/cm^3 of the log density over the depth interval studied.

2). The vertical gradient at the site is anomalously high.

Two hypotheses can explain these observations. Either the SSSDP well is surrounded by higher density material between 3000 and 6000 feet, or there is low density material near it at a range of 0 to 2000 feet. Because of the high densities observed in the SSSDP hole, the second hypothesis is preferred. Preliminary models constrained by the surface gravity indicate that the low density zone is within 500 feet of the well, and may represent the outer boundary of the zone where paleo-temperatures exceeded those presently detected in the SSSDP well.

SSSDP: Physical and Chemical Laboratory Studies of Cores from the Salton Sea Scientific Drilling Project
(W. D. Daily and W. Lin)

We plan to measure the ultrasonic wave velocities, electrical resistivity, and brine permeability on SSSDP samples under in situ pressure and temperature conditions. The experiment will provide insight into the interpretation of well log and surface geophysical data, understanding of brine transport mechanism, interpretation of flow tests, and the extrapolation of properties measured in the borehole to greater depths.

So far a SSSDP siltstone core from 1158-m depth has been studied in the laboratory to determine electrical resistivity, ultrasonic velocities, and brine permeability at pressures and temperatures close to the estimated borehole conditions. The maximum pressure and temperature during the experiment were 50 MPa and 245°C respectively. A synthetic brine with 13.6 weight percent NaCl, 7.5 weight percent $CaCl_2$ and 3.2 weight percent KCl was used as pore fluid. The sample had an effective porosity of 8.7%. At the mid-plane of the sample, impedance imaging was used to map the spatial variation of resistivity as a function of time. Also, in the same plane ultrasonic tomography was used to map the spatial variation of P-wave velocity. In addition to these tomographs, resistivity was measured with 6 pairs of electrodes along the sample axis. P-wave and S-wave velocities were also measured along the sample axis. A second sample from a depth of about 3000 feet has been assembled in the pressure vessel, and is being studied.

Continental Drilling Data Management Unit
(G. Pawloski and P.Kasameyer)

A commercial database system designed for handling well logs, with data from about 15 wells from the Salton Sea Geothermal Field, was taken to the SSSDP site before drilling began. It was maintained on site to provide researchers access to previously collected data, and to construct an on-site data base of the data from the SSSDP well. Livermore staff traveled to the site periodically to set up and maintain the system, to enter data into it during logging runs, and to train the on-site USGS geologists in its operation.

All Schlumberger logs, all "standard" USGS logs run in the hole, and the mud logger's lithologic reports were entered into the data base system, making the logs rapidly available for inspection, manipulation and display on site. After the field activities were completed, the data base system was returned to Livermore where the data were checked, depth shifted to correct for depth errors, and archived. Figures were made for the "Preliminary Data Report " published by the USGS. (Paillet, 1986)

The well logging data from the SSSDP are currently being studied by Hsuang-Yuen Lei, a graduate student at the University of California at Riverside, in collaboration with Paul Kasameyer and Robin Newmark of LLNL. The purpose of the work is to develop log analysis methods that will allow the degree of metamorphism to be estimated without examining samples, and to understand the physical changes caused by metamorphism.

In summary, the data management program has ensured that the logging data from the SSSDP well were available to scientists during the drilling, were archived in an accessible manner, and are being studied to understand the hydrothermal system at the Salton Sea.

Seismic Studies of Possible Magma Injection and Magma Chambers in the Long Valley Region
(J. J. Zucca and P. W. Kasameyer)

We performed a passive seismic experiment in the Long Valley caldera region of California. A small network of 14 three-component digital seismographs in the Mono Craters area recorded small earthquakes located to the south of Long Valley. One earthquake recorded shows a clear, high amplitude phase arriving between the normal P and S arrivals. A similar phase has been recorded by other researchers corroborating our observation. We interpret the phase to be a reflection that has not been significantly laterally refracted. The appearance of this phase is dependent on azimuth which suggests that the reflector is quite heterogeneous. Using amplitude and travel time modeling we suggest that the phase is a P to P reflection from the base of a low-velocity layer with a high-velocity floor that extends to near the base of the crust (Zucca et al, 1987). Recent observations by Peppin and Delaplain (1987) have indicated that these phases may be P-S conversions in the upper crust. We are modeling this data to test the competing ideas.

A second passive seismic experiment has been planned for late summer 1987. Recent observations of teleseismic P waves recorded in Long Valley show large anomalous arrivals on the horizontal components. These phases may be due to converted energy from interfaces five to eight kilometers below the surface of the caldera. These observations could provide a new method for mapping the magma chamber thought to exist in the region. The exact nature of these arrivals needs to be confirmed. We plan to utilize the new LLNL local seismic network to measure both the phase velocities and particle motions of these arrivals. Ten, three-component stations using high-quality 1 Hz seismometers will be deployed in the Resurgent Dome area of Long Valley. Three to six weeks of continuous recording should provide an adequate teleseismic data set to determine the nature of these arrivals.

Basic studies of rock properties of interest to geothermal

Electrical Conductivity, Temperature, and Radiative Transport in the Earth
(A. G. Duba) (Joint research with T. J. Shankland at LANL)

The thermoelectric effect S and electrical conductivity σ in the mantle minerals olivine and pyroxene are being measured as a function of temperature, orientation, oxygen fugacity, and iron content. The results apply to inference of upper mantle temperatures from electrical data. Although there are seismic models to explain the low velocity zone (LVZ) as a solid-state phenomenon not requiring partial melting, the most well-constrained laboratory electrical measurements are more consistent with the partial melting hypothesis for the high conductivity layer (HCL) apparently associated with the LVZ. If the LVZ/HCL is not a partial melt layer, then mantle geotherms would be considerably lower than previously inferred on the basis of a partial melt zone under extensive regions of the earth. Hence, it is necessary to better understand electrical conduction in mantle minerals to find how electrical data constrain low temperature geotherms suggested by solid state explanations of the LVZ and thus to better define broad geothermal regimes.

In addition to measuring S and σ in the three principal directions in olivine from San Carlos, Arizona, at 1200° to 1500°C under controlled oxygen fugacity, we have obtained most of this information for the related, iron-free mineral forsterite under oxidizing and reducing conditions.

We have used these results in two ways. One has been to use spatial averages to obtain a best-fitting conductivity-temperature curve for determining upper bounds on mantle temperatures from field electrical work. The other was to argue for a high-temperature mantle geotherm on the basis that the abrupt rise in mantle conductivity at the HCL is due to partial melt.

Attenuation and Dispersion in Partially Saturated Rocks
(J. G. Berryman, B. P. Bonner, R. C., Y. Chin, G. W. Hedstrom, and L. Thigpen)

The objective of this project is to combine theory and experiment to analyze attenuation and dispersion of waves in partially or fully saturated rocks over a broad range of frequencies. The techniques developed in this work will be applicable to many basic problems in energy recovery, particularly hydrocarbon and geothermal exploration and resource assessment. This project has continuing experimental and theoretical components:

1) Our recent experimental efforts have concentrated on verifying theoretical predictions for wave propagation in fluid-saturated porous media. Biot's theory requires a description of the internal porosity, which we wish to measure independently to test the theory. Measurements of the electrical conductivity of saturated rock and the saturating pore fluid can be used to estimate the tortuosity of the pore space.

2) We have also continued our collaboration with the Ultrasonics Group, Department of Welding Engineering, Ohio State University. Experimental techniques used ordinarily for non-destructive evaluation have proven useful for investigating saturated porous media. Our attention is directed mainly at the properties of waves that propagate in the vicinity of interfaces between fluids and saturated porous rock. We have investigated the acoustic properties of high porosity foams to test the validity of Biot's theory for porosities up to 90 %.

3) Recent theoretical efforts have led to a comprehensive theory of wave propagation in partially saturated porous media. A new explanation of the observed magnitude of the attenuation of waves in partially saturated porous media has been proposed based on a local-flow generalization of Biot's theory. This idea provides very plausible explanations of the discrepancies previously observed between theory and experiment. It also shows that acoustical methods may not be used directly to measure global permeability of rocks, although bounds on permeability may be obtained from attenuation measurements. The image processing method for analyzing rock topological structure being developed here has also been shown to be a promising method for determining the values of the local permeability and formation factor required in a predictive theory.

Rock Mechanics
(H. C. Heard, B. Bonner, W. B. Durham and F. J. Ryerson)

This program includes high pressure - high temperature research into the effects of porosity on the mechanical and transport properties of rocks. We are pursuing two subtasks: rock joint profiling in the laboratory, and a study of thermal cracking in rocks as a function of pressure and temperature.

The rock joint profiling is performed using a high-precision, computer-controlled surface profiling device recently constructed specifically for this task. Fracture surfaces are digitized with the instrument, and joints are reconstructed by comparing the two fracture surfaces that make up the joint. We refer to the mathematical function formed by subtracting one surface profile from its matching profile as the "composite topography" of a joint. Theory suggests that joint stiffness and fluid flow depend not so much on joint roughness as on the composite topography. This theory was tested by studying naturally fractured samples from the Fenton Hill Hot Dry Rock site (Brown, et al., 1986). We found that one of the most important characteristics of a joint is how "well" its two faces are correlated. Joints that are highly correlated tend to be less permeable and stiffer than joints that are less correlated. Virtually all fracture surfaces mapped thus far are fractal-like surfaces, self-similar from the finest scale we can resolve up to the scale of the sample size. It also turns out that the composite topography is a fractal, but only below the scale, known as the correlation length, at which the joint surfaces no longer match. Correlation lengths for surfaces measured to date fall in the range 0.5 to 5 mm/

The second subtask is an investigation of microcrack generation and velocity changes in granite during heating while under confining pressure. The total number of acoustic emission (AE) events as a function of temperature for three Westerly samples heated to 300°C under confining pressures of 7, 28 and 55 MPa show very little activity up to 100°C. Then the critical temperature for onset of significant acoustic emissions varies linearly with the confining pressure. Confining pressure is incrementally less effective in suppressing thermally-induced cracks. This is the first successful application of the AE technique at elevated temperature and pressure.

The largest compressional velocity decrease and greatest difference between heating and cooling was recorded during the 7 MPa test. The effect of confining pressure is to reduce the velocity decrease and hysteresis. The temperature at which the velocity upon cooling returns to the value it had during heating is greater at higher confining pressures. The smaller hysteresis at higher confining pressures is consistent with the newly created cracks having closure pressures below 40 MPa. The difference in compressional velocity between the heating and cooling portions of the thermal cycle seems to be a very sensitive indicator of the crack porosity in the rock. This difference could be exploited to monitor the physical state of a waste repository by seismic techniques.

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