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THE MORE-THAN-CLOUD AND SUCCESSOR PROJECTS: INTERNATIONAL JOINT RESEARCH ON NEW MAPPING AND HDR/HWR RESERVOIR DEVELOPMENT TECHNOLOGIES

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ABSTRACT

Understanding of the geothermal reservoir, especially characterization of the cracks that form a subsurface fracture network, is essential for design, creation and control of engineered Hot Dry Rock/Hot Wet Rock (HDR/HWR) systems. Prediction of the energy production and lifetime remains a fundamental unsolved problem. Two projects are now aimed at solving these problems. While funded by Japan's NEDO, they bring together researchers from France, Germany, Japan, Switzerland, United Kingdom, and the U.S. They are focusing upon interdisciplinary work between seismology, reservoir engineering and rock mechanics to develop the required new methods.

1. BACKGROUND OF THE MORE-THAN-CLOUD (MTC) AND POST-MTC PROJECTS

Obtaining a comprehensive understanding of a geothermal reservoir, and in particular, obtaining a complete characterization of the crack system, is essential for the design, creation, control, and optimized exploitation of HDR/HWR systems. It is generally accepted that Acoustic Emission (AE) and Microseismic (MS) techniques are the only methods of practical use for obtaining detailed information about deep geothermal reservoirs, particularly at distant locations from boreholes. Seismic techniques that use artificial sources cannot emit sufficient energy into deep reservoir regions at the relatively high frequency needed for adequate resolution. AE/MS mapping techniques have therefore been used widely in all HDR/HWR projects. One of the problems with AE/MS mapping techniques is the reliability of the event location accuracy. In every HDR/HWR project, AE/MS source locations were mapped and images of the reservoir presented, but normally they have been distributed as a "cloud", and provide a blurred, fuzzy image of the reservoir.

2. MTC PROJECT

In February, 1992, international scientists working on seismic imaging techniques received an invitation to start an international collaborative project on seismic imaging from Professor Hiroaki Niitsuma, Tohoku University. The project was named "MTC Project" because the goal of the project was to establish technologies to provide detailed images. For three years, beginning in 1995, the MTC project received direct funding at a level of 30,000,000 Yen per year from NEDO (the New Energy and Industrial Development Organization of Japan). The MESSC (Ministry of Education, Science, Sports and Culture) funded an additional 9,195,000 Yen for academic basic research for FY 96-97.

2.1 Participants in the MTC Project

Research members of the MTC Project are listed in Table1. In addition to the seven research groups funded by NEDO, observers from Japan, France, Sweden, Germany, Australia and Switzerland joined the Project. The total number of researchers that contributed to the Project is 41, excluding students.

2.2 Major accomplishments of the MTC Project

Collapsing method
An AE/MS event is one kind of random process because the signal is contaminated by random noise and the estimated location is affected by the often undetermined velocity structure. A concept to relocate seismic sources by statistical optimization, called the "collapsing method" has been developed by R. Jones of CSMA (Jones and Stewart, 1997). In the collapsing method, seismic locations are moved inside their uncertainty confidence ellipsoid until a simplified picture of earthquake cloud is obtained. Figure 1 shows original and relocated (collapsed) locations of microseismic events from Mammoth Lake, USA. The fault structure is clearly revealed by the collapsing method.

Doublet/cluster analysis
During seismic analysis we sometimes observe a group of events having similar waveforms, although their time of occurrence is different. This group of events is called a doublet, multiplet or cluster. As it is reasonable to consider that doublets have the same source mechanism, we expect to obtain new knowledge on dynamic behavior of a fracture system by the temporal-spatial analysis and source mechanism analysis of doublets. Tezuka and Niitsuma (1997) precisely

mapped doublets/multiplets at Hijiori by cross-spectrum analysis. Figure 2 shows: (a) locations determined by conventional seismic mapping, and (b) locations determined by doublet analysis. The injection well (center) and production wells (to the sides) are shown, as well as reservoir production feed points (solid rectangles in the production wells). More precise structure appeared after doublet mapping and this result has made it possible to correlate AE/MS cloud and feed points in the borehole.

AE/MS reflection method

Recently, the existence of reservoirs at greater than typical depths has been suggested, and a measurement technique to characterize such very deep reservoirs is an important key to exploit these reservoirs. Soma and Niitsuma, (1997) developed a method to discriminate the reflected phase from the AE/MS signal by analysis of three dimensional hodograms. Figure 3 is a reflection image of Kakkonda geothermal field, Japan by the AE/MS reflection method. The top and inside structures of the deeper reservoir in this field was successfully imaged by this new technique.

3. The Post-MTC Project

In 1998, recognizing the success of the MTC project, NEDO decided to fund a successor project which would focus international collaboration upon integration of AE/MS mapping with rock mechanics and reservoir engineering. The particular concern was with prediction of the energy production and lifetime of HDR/HWR reservoirs. Heat production tests require months, if not years, of reservoir testing. But such long operating times retard the commercial development of engineered reservoirs because the developers must invest considerable money to install the wells, piping and turbines without knowing how long the reservoir will produce the energy.

3.1 Participants in Post-MTC project

Research groups are listed in table 2. There are 8 groups with a total of 29 researchers.

3.2 First Year Accomplishments of Post MTC Project

Microseismicity

The AE reflection method (Soma and Niitsuma, 1997) is one of the most feasible methods to delineate structures inside the HDR/HWR reservoirs. The AE reflection method was applied to data sets from Soultz and Kakkonda, and structures inside/around reservoir were imaged. However the AE reflection method was unable to resolve nearly vertical fractures, which are considered to be predominant structures at Soultz. In 1998, the research group in Soultz and Tohoku University collaborated to image vertical reflectors using microseismicity as a source. This method was applied to the Soultz data set and some vertical structures appeared in the reflection image showing feasibility of this new idea.

Tracers

It is possible to estimate the effective temperature along an injection-production pathway by injecting a stable tracer in combination with a reactive tracer having a known decay rate. First, the reactive and conservative tracers are injected simultaneously at the injection well. The concentrations of the two tracers are then measured over time at the production well. Then, by inverse (trial and error) modeling, a temperature is selected that predicts the measured decay of the reactive tracer.. This method was verified in a tracer test in the hydrothermal system at Steamboat Hills, Nevada, USA (Rose et al., 1999). Three fluorescent compounds that show promise for use as reactive tracers are the fluorescein halides 2',4',5',7'-tetrachlorofluorescein, eosin Y, and erythrosine B, where the latter two are the bromide and iodide derivatives, respectively. Composite tracers, perhaps using temperature sensitive coatings surrounding colloids and other stable tracers, show excellent promise to provide important reservoir properties such as the temperature of the surface contact area of host rock. For example, simple organic compounds will have flow characteristics that differ with water-soluble macromolecular polymers or dispersible colloidal materials.

Flow in reservoir fractures

When water is injected into joints in rock masses, several types of joint deformations can take place. At first the pressure rise in the joint is small enough that the joint does not actually open. Nevertheless, the effective closure stress is reduced, the tightness of joint closure is lessened, and effective opening, or aperture, of the joint is increased. If the fluid pressure rise is small enough, the aperture can still be treated as nearly constant, and the transient pressure response therefore follows the usual laws of linear diffusion. But if the pressure increase is large, aperture increases must be accounted for, and the flow will be affected by nonlinear diffusion due to pressure-dependent aperture, as well as an additional storativity term due to aperture increase. Eventually the fluid pressure may attain a value equal to the total earth stress acting normal to the joint, and the opposing surfaces of the rock that meet at the joint can actually part, or "liftoff." Then the flow equation becomes so nonlinear that pressure pulses are no longer transmitted in a smooth, diffusive manner but more like a propagating shock wave. Analytical solutions for each of these situations were developed.

The easy-to-use Geocrack code (Swenson, 1998) was extended to three dimensional geometries for fluid flow. Initial calculations demonstrate the beneficial effects of thermal stress cracking. Additional calculations show that such tracer tests are particularly diagnostic, as they are greatly affected by cooling of the reservoir. Another model , GEOTH3D, takes account of a reservoir structure modeled by porous media with spatially variable permeability which is determined with the aid of AE measurement at an HDR site and local permeability measurement around the wells. Based on the permeability distribution, the GEOTH3D code enables one to compute 3D distribution of Darcy velocity, pressure and temperature, including the interaction between flow and temperature. A modified permeability model was used to evaluate water recovery assuming a new production well was drilled in the Ogachi geothermal site. The results show that the total recovery could be increased up to 44.5% if a new production well were operated with rather small back-pressure of 0.2MPa and if a hypothetical brick-like zone were fractured to yield highest permeability.

CONCLUSIONS

(1) Practical international joint research has been made using a real-time collaboration system through the Internet, and its effectiveness demonstrated by several new developments in reservoir imaging and engineering.

(2) Advanced mapping techniques were developed,.

(3) New knowledge on HDR/HWR geothermal reservoirs was obtained.

(4) Common understanding on the advantages and disadvantages of each AE/MS technique has been brought to the research members.

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Table-1: Member of the MTC Project (*; observer)

Organization	Group leader	Research member
Graduate School of Engineering, Tohoku University (Japan)	Hiroaki Niitsuma (Representative)	H. Asanuma, H. Moriya, N. Soma, K. Nagano, A. Le□niak, R.C.Stewart
Socomine (France)	Roy Baria	A. Jupe, A. Beauce, P. Starzec, C. Hulot
New Mexico Tech. (USA)	Michael Fehler	W. Scott Phillips, L. House, D. Alde, J. Rutledge, R. Aster, C. Rowe
CSM Associates (UK)	Andrew Green	R. Jones, S. Wilson
Institute of Fluid Science, Tohoku University (Japan)	Kazuo Hayashi	T. Ito, H. Saito
CRIEPI (Japan)	Hideshi Kaieda	S. Sasaki
JAPEX (Japan)	Kazuhiko Tezuka	
IPGP (France)*	F. Cornet	E. Gaucher
Chalmers Univ. (Sweden)*	T. Wallroth	P. Starzec
BGR (Germany)*	R. Jung	
ETH (Switzerland)*	K. Evans	
JMC Geo-E (Japan) *	M. Tateno	
NIRE (Japan)*	I. Matsunaga	
Australian National Univ.*	D. Wyborn	P.Chopra

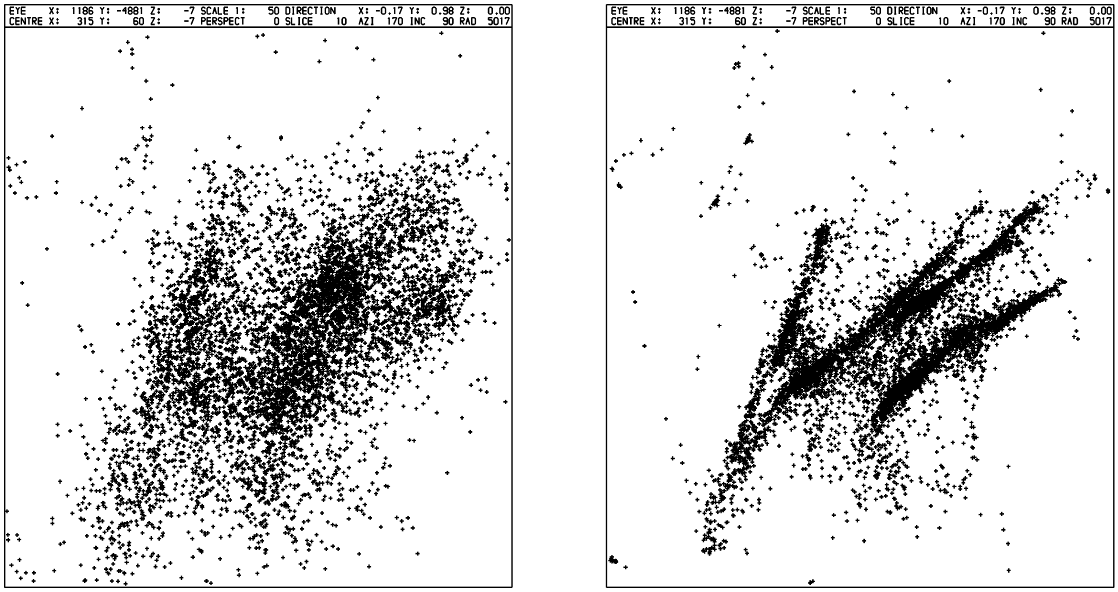

Fig-1: Location of microseismicity at Manmoth Lake, USA
Left: conventional technique (JHD), right; collapsing method

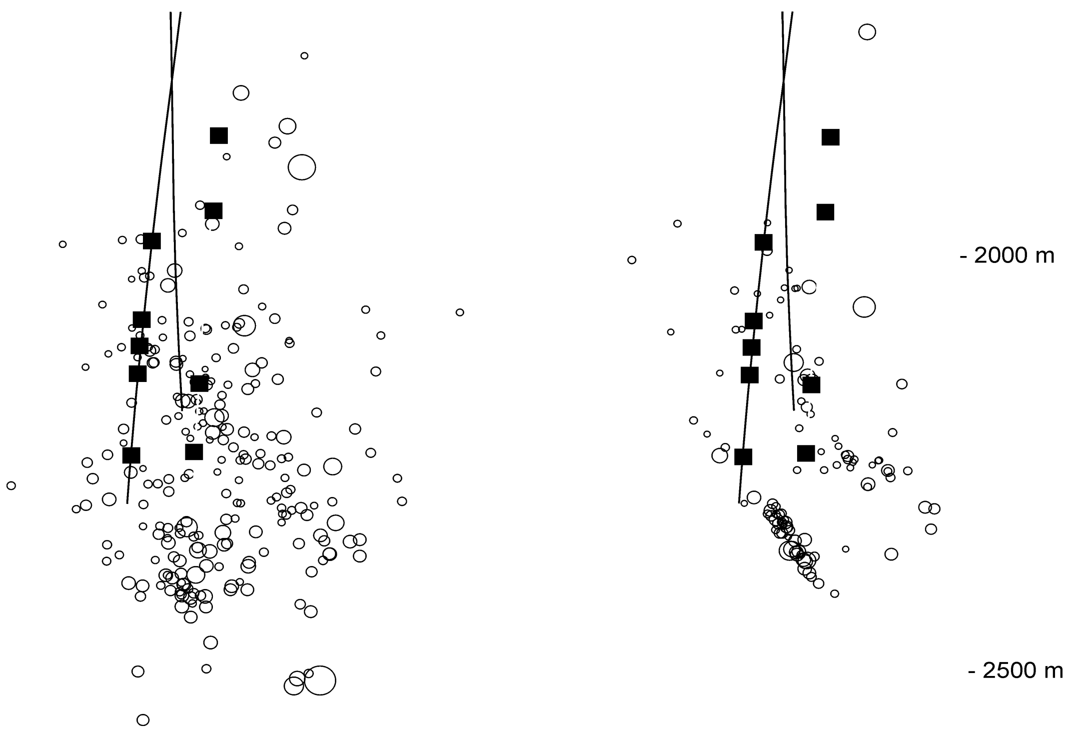

Fig-2: Location of microseismicity at Hijiori, Japan
Left: conventional technique, right; doublet analysis

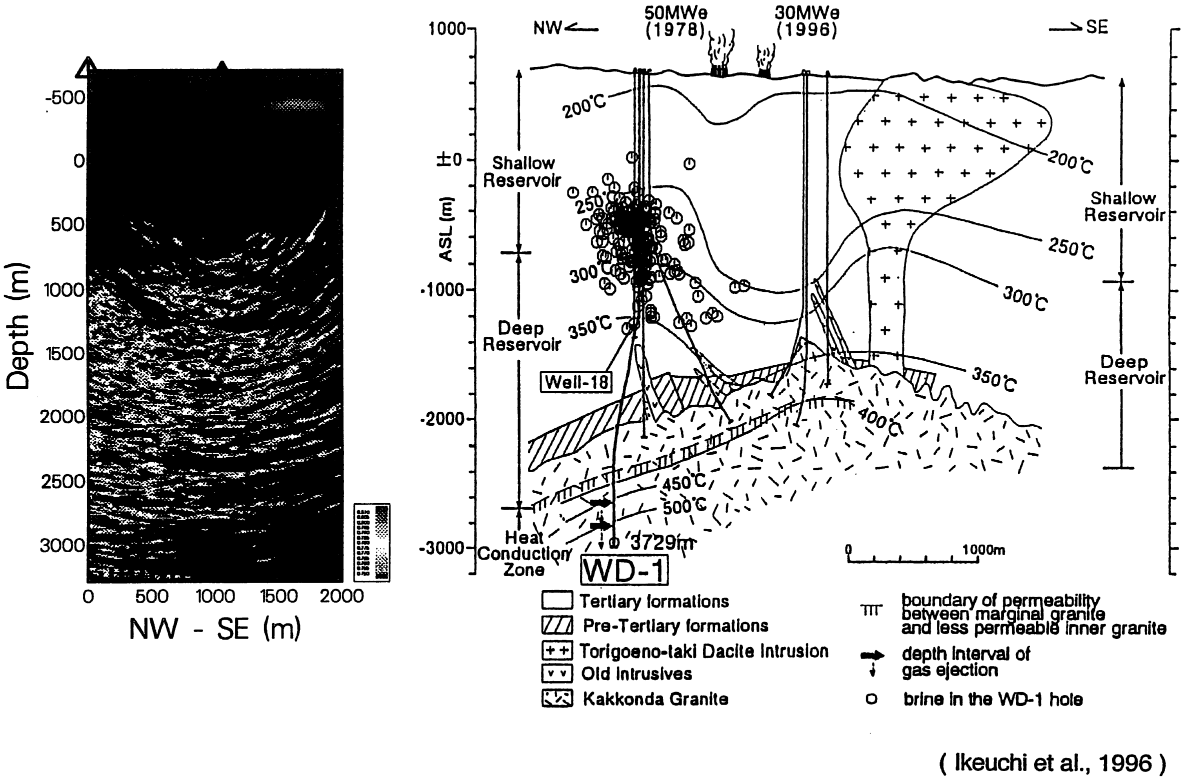

Fig-3: Reflection image at Kakkonda, Japan by the AE reflection method

Table-2: Member of the post-MTC Project

Organization	Group Leader	Research members
US Team	Hugh Murphy	D. Brown, M. Fehler, P. Rose, D. Swenson
Tohoku University Team	Hiroshi Asanuma	H. Niitsuma, K. Hayashi, T. Ito, H. Moriya, H. Saito, K. Nagano
CSM Associates Team	Roger Parker	A. Jupe, R. Jones
Soultz Team	Reinhard Jung	R. Baria, N. Soma, S. Reamer
Swiss Team	Robert Hopkirk	K. Evans
CRIEPI Team	Kenzo Kiho	H. Kaieda, K. Shin, H. Suenaga
JAPEX Team	Kazuhiko Tezuka	T. Nakayama, K. Watanabe
NIRE Team	Norio Tenma	