PREDICTING FRACTURE CHARACTERISTICS IN VOLCANIC ENVIRONMENTS AS A GUIDE TO LOCATING EGS RESERVOIRS.

PROJECT SUMMARY

The identification and characterization of geothermal targets for EGS development is required to meet DOE's goal of 40,000 megawatts. Few areas contain the potential for the rapid growth that will be needed. The most attractive candidate regions are the Cascade Range, with its numerous active volcanic systems, and the Salton Trough. Deep drilling at several sites within the Cascade Range where surface manifestations are only weakly developed has demonstrated that extensive areas of hot rock lie beneath its volcanic features. Most of these wells have encountered low permeability rocks suitable for the development of large EGS reservoirs. Despite its potential, the province is underdeveloped, poorly explored, and inadequately understood. This project addresses the techniques required for locating and developing of EGS reservoirs in complex volcanic terrains.

Hydrofracturing is currently the best technique for forming EGS reservoirs. The permeability enhancement that can be achieved is dependant on the characteristics of the natural fracture networks and the stress distributions. In volcanic terrains, local stress distributions reflect the interactions of regional tectonic stresses with stresses induced by magmatic activity and increasing overburden thickness. Heterogeneities in rock lithologies and rheologies, hydrothermal alteration and temperature further influence fracture characteristics and fluid flow. Because drilling accounts for a major percentage of EGS development costs, the best means of reducing costs is to reduce the number of wells drilled. Better methods for targeting wells and improving well productivities are needed. The goal of this investigation is to develop and test predictive methods for extrapolating stress distributions and fracture characteristics obtained from isolated well bore measurements to areas where subsurface data is not available. An integrated approach that combines fracture and rock property data with numerical simulations is proposed. Improving reservoir performance addresses Objective 1 of the solicitation: "Increase the identified economically-viable domestic geothermal resources to 40,000 megawatts". A reduction in the number of wells will lead directly to a decrease in the price of electricity (Objective 2 of the solicitation).

This study will initially focus on the Glass Mountain geothermal area, located on Medicine Lake Volcano in northern California. This area was selected by Calpine and the DOE for EGS development. It represents the best site for testing the proposed techniques because an extensive collection of cores, cuttings and geological, geochemical and geophysical data is available for evaluating subsurface conditions. The well samples will be used to determine the characteristics of the fracture systems, their origins, and the factors that control their ability to transmit fluids. In-situ stress distributions will be calculated from measurements made on the core samples. A structural model of the area will be developed from these data. The model will be used to calculate stresses, fracture types and fracture distributions. The predicted stress and fracture distributions will be evaluated through comparison with observations in selected test core holes that are not used in the calculations. Work performed on this project will represent a cooperative effort between EGI and the Calpine Corporation. Dr. J. Moore will act as the Principal Investigator. Mr. J. Hulen and Dr. Michal Nemčok will serve as Co-Principal Investigators.

RELEVANCE AND JUSTIFICATION

Increases in the production of geothermal energy to 40,000 Mw will require the identification and characterization of sites appropriate for the development of EGS reservoirs. The Cascade Range, a region of young volcanism, and the Salton Trough hold the greatest potential for the large scale development of EGS reservoirs in the U.S. This proposal focuses on the Cascade Range, which extends from Mt. Meager in British Columbia southward for over 1000 km to Lassen Peak in northern California. Although hot springs throughout the length of the range document widespread upflow of thermal fluids, deep drilling suggests that much of the potential of the Cascade Range is hidden. At Newberry Crater, Medicine Lake Volcano, and Mt. Meager, where surficial manifestations are feeble or nonexistent, wells have confirmed the existence of large regions of accessible hot rock with temperatures locally exceeding 250°C. However, only the wells at Telegraph Flat on Medicine Lake Volcano have demonstrated commercial permeabilities, and these permeabilities are very modest compared to permeabilities in some of the world's best volcanic-hosted systems. Low permeabilities appear to be common throughout much of the Cascade Range.

Experiments conducted in the U.S., Europe and Japan demonstrate that growth and development of EGS reservoirs by hydrofracturing is controlled by the stress field and the geometry of the pre-existing fracture networks. While these experiments demonstrate the feasibility of forming EGS reservoirs, only nominal flow rates were attained. It is apparent from these tests that significant increases in geothermal production from EGS reservoirs will only be achieved if large areas of naturally fractured rock can be incorporated into the growing reservoir. One implication of this conclusion is that relatively large areas of potential reservoir rock will have to be evaluated to achieve economic viability and high reservoir performance. Regions marginal to commercial hydrothermal systems hold the greatest near-term potential.

Stress distributions and fracture characteristics in volcanic terrains are the result of interactions between the regional tectonic framework, stresses induced by subvolcanic intrusives, heterogeneities in rock lithologies and rheologies, hydrothermal alteration, overburden thickness and temperature. The goal of this proposal is to develop and test methods that combine geologic and appropriate rock mechanics data with numerical simulations to define, model and predict locations for EGS reservoir development. Extrapolating in-situ stress and fracture measurements from isolated bore holes to areas where subsurface data is not available is the key to achieving this goal. This proposal directly addresses Goal 1 of the solicitation to "Increase the identified economically-viable domestic geothermal resources to 40,000 megawatts" by reducing the risk and cost of EGS development through better target selection and Goal 2 of "reducing the levelized price of electricity" by reducing drilling and development costs.

The initial studies will focus on the Glass Mountain geothermal area, located on Medicine Lake Volcano, in northern California. This region includes Fourmile Hill, which is considered an appropriate site for EGS development by the Calpine Corporation and the DOE. Glass Mountain is particularly well suited for study because: 1) It is typical of much of the Cascade Range and thus the technology can be readily transferred to other areas; 2) It is arguably the best documented thermal area in the Cascade Range. Core and subsurface data are available to develop, test and refine laboratory, theoretical and numerical models; and 3) There is considerable industry interest in the Cascade Range. Thus, it is anticipated that these studies will have a direct impact on future development at numerous sites within the Cascade Range, including Glass Mountain and Mt. Meager, where exploration activities are currently underway. Characterizing the subsurface fracture networks is a necessary first step in developing the techniques that will lead to enhanced productivities. The proposed work addresses topical research areas A (Techniques and tools for fracture mapping and analysis) and D (Techniques to create, characterize, stimulate and evaluate fractures and fracture networks)

PROJECT DESCRIPTION

Approach

The concept proposed here is that the characteristics of fracture networks and the stress distributions in volcanic rocks outside the bore hole can be adequately defined, modeled and predicted from geologic and appropriate rock mechanics data. The basic geologic data will be obtained from investigations of core holes drilled throughout the area. Core samples are essential because they provide information on fracture characteristics (e.g. aperture, porosity, permeability, age relationships and kinematics) and mineralogic relationships that cannot be obtained from cuttings (e.g. Nemčok and Gayer, 1996; Nemčok and Lisle, 1995; Nemčok et al., 1995, 1999; Moore et al., 2000). The paleomagnetic signature of selected core samples will be used to orient fractures and determine in-situ stress distributions. A structural model of the area will then be developed and used to calculate stresses, fracture types and fracture distributions. The predicted stress and fracture distributions will be evaluated through comparison with observations in selected core holes that are not used in the calculations. Thus some of the core holes will provide a "blind test" of the results.

The feasibility of this approach has been convincingly demonstrated by the results of recent investigations of the Schneeren-Husum gas field (Nemčok, 2002) and the unique and successful investigations conducted with the Karaha Bodas Co. LLC (Caithness Energy) on the volcanic-hosted geothermal system at Karaha-Telaga Bodas (see Christensen et al., 2002; Nemčok et al., 2003, 2004 and references therein).

The Schneeren-Husum gas field in Germany is a structurally controlled reservoir developed in Upper Carboniferous sandstones. In this study, core and image logs were utilized to calculate stress distributions within a complex strike-slip environment. The results were tested by comparing the modeled stress fields with data from wells that were not used in the calculations. Excellent correspondence between the modeled and predicted stress distributions was obtained.

Karaha-Telaga Bodas is a young vapor-dominated volcanic-hosted geothermal system in western Java. Petrologic, geochemical and fracture data were combined with downhole pressure and temperature measurements to define the system's time-temperature-composition and structural evolution. Mineral relationships and ^{14}C dating indicate the system evolved very rapidly, being liquid-dominated only for a short period between 6000 and 4000 y BP before becoming vapor-dominated. Fractures in two 1-km core holes and those represented in electric image logs from two additional deep wells were described. Data from the core holes were used to characterize the permeability structure and fracture evolution of the cap rock and reservoir. Fractures were evaluated with respect to host lithology, orientation, type (e.g. extensional, normal fault, strike slip fault etc.) and mineralogy. Well defined mineral parageneses were used to constrain the relative ages of the fractures. Stress distributions determined from an analysis of the electric image logs and the ratio of stress magnitudes (see method in Nemčok and Gayer, 1996) were used to calculate slip vectors, fracture kinematics, the resolved normal and shear stresses acting upon each fracture and the fracture's tendency to dilate and slip (see methods in Wallace, 1951; Nemčok and Lisle, 1995; Nemčok et al., 2001a, b).

Karaha-Telaga Bodas and Glass Mountain share similarities in the character of the volcanic complexes, presence of granitic intrusions and the degree and extent of the hydrothermal alteration. In addition, both systems appear to be relatively young. The following conclusions from Karaha-Telaga Bodas are particularly pertinent:

1. We have shown, for the first time, how and why vapor-dominated geothermal systems form in volcanic terrains. Vapor-dominated systems are the most valuable resource type. The results of

our investigations indicate that vapor-dominated regimes form as a result of decompression triggered by catastrophic slope failure of the volcanic edifice. These concepts are directly applicable to the Cascades and other volcanic terrains.

2. Studies of fracture wall structures show that the orientation of the stress field has remained stable since the fractures formed.
3. There is a change in the local stress regime with depth. Normal faults, tensile, fractures. sinistral and dextral strike-slip faults and oblique sinistral and dextral strike-slip faults with a normal component of displacement occur in the caprock. In contrast, only normal and tensile fractures occur in the reservoir. The change from a strike slip regime with $\sigma_1 \geq \sigma_2 \gg \sigma_3$ to an extensional stress regime with $\sigma_1 \gg \sigma_2 \geq \sigma_3$ reflects the increase in overburden thickness, which causes a change in the principal stress magnitudes but not in their orientation. This stress change results in wider fracture apertures and increases the likelihood of more dilatant fractures in the deeper reservoir rocks, which improve reservoir quality. Thus the stress regime appears to play a strong role in reservoir behavior.
4. Productive and nonproductive fractures can be distinguished on the basis of their calculated tendencies to slip and dilate and on their ability to withstand resolved normal stresses. These characteristics provide information on a fracture's tendency to reactivate, its ability to transmit fluids and its response to hydrofracturing. The majority of the productive fractures were among those that were most prone to dilate or slip.
5. The best productive fractures are tensile fractures and normal faults with strikes roughly perpendicular to the minimum compressive stress, which trends 98°. Ideally oriented fractures have strikes of ~8° and steep dips. These fractures have a tendency to achieve maximum possible apertures.
6. There is no apparent relationship between fracture density and fluid entries. Fracture densities of 5 per 10 m characterize both productive and nonproductive zones.
7. As the system evolved, descending waters deposited calcite and anhydrite. Progressive sealing of the fractures resulted in downward growth of the cap rock and a reduction in shallow permeabilities.

Novelty of the Approach

The proposed investigation represents a comprehensive and integrated effort combining field data, observations on core and cuttings samples, rock mechanics data, the results of laboratory analyses, physical process-driven interpretations and numerical validation. We believe, based on a literature search, that the approach we will utilize to predict stress distributions and fracture characteristics has never been utilized in the analysis of a geothermal reservoir, either EGS or hydrothermal, as is the use of "set aside" data sets as an ultimate test of accuracy in defining future targets.

Overview of the Glass Mountain Thermal Area

The Glass Mountain thermal area (KGRA) is located on Medicine Lake Volcano, on the eastern edge of the Cascade Range, 50 km east-northeast of Mt. Shasta. It is the largest known commercially producible, but wholly undeveloped, high-temperature geothermal resource in the U.S. The geology and geothermal features of the area are described by Donnaly-Nolan (1988, 1990), Hulen and Lutz (1999), Iovenitti and Hill (1997) and Lutz et al. (2000).

Since the 1980s, 26 thermal gradient and four deep wells have been drilled on Medicine Lake Volcano. Borehole measurements have defined an area covering 104 km^2 with temperatures of 260°C at depths of <1220 m. This region includes the Telegraph Flat area, which contains a demonstrated commercial-grade hydrothermal system, and the Fourmile Hill area 8.8 km away, where hot but low permeability rocks were encountered at depth.

Medicine Lake Volcano is a Pleistocene to Holocene shield volcano approximately 32 km across. The volcano contains a broad summit depression, which has been interpreted as a caldera although there is little evidence of collapse (Hulen and Lutz, 1999). Despite the large size of the area, and the high temperatures at depth, the system is essentially blind, with only a single weak fumarole known as the Hot Spot.

The thermal history of the area appears to be long and complex. The volcanic suite is bimodal consisting mainly of rhyolite and basalt with lesser dacite, and andesite. Flows, tuffs, and epiclastic deposits are present. The youngest rocks are rhyolitic lava flows, some erupted as recently as ~1000 years BP. These flows occur near the summit of the volcano and document the presence of recent magmatic input. Early to Late Holocene basalts erupted from vents at lower elevations. Granitic rocks believed to have been emplaced at ~300,000 Ka, were encountered at depth in the Telegraph Flat area.

Heat and fluids related the granite produced hornfelsic textures in the volcanic rocks and deposited vein minerals at temperatures >315°C. Younger minerals were deposited as the system cooled, but the characteristics of these mineral assemblages and number of thermal cycles that have affected the rocks has not been established. Investigations of other volcanic hosted systems (e. g. Tiwi, Karaha-Telaga Bodas; Moore et al. 2000; 2002) suggest that individual heating and cooling cycles are likely to be relatively short lived (<a few thousand to 10s of thousands of years) but that mineral deposition and fracture sealing can happen very rapidly, with significant long term impacts on rock permeabilities.

The structural setting of the volcano reflects its position on the Modoc Plateau, a volcanic highland formed in the extensional environment of the Cascade Range-Basin and Range transition zone. Several sets of faults are present. NW-SE and N-S striking faults are common north and south of the volcano and their intersection may have exerted control on the volcano's location. NE-SW striking extensional faults dominate at Little Glass Mountain, one of the Late Holocene rhyolitic flows near the summit of the volcano. The significance of these faults, however, with respect to the permeability structure at Glass Mountain is poorly understood.

Availability and Scope of Data

A very comprehensive suite of data, samples, and analyses is available for this project. The data package includes more than 17,500 m of core and cuttings, the results of downhole surveys (pressure, temperature, spinner data), well test data, geochemical analyses (chemical and isotopic analyses of fluids and rocks, soil gas surveys), results of geophysical surveys (MT, resistivity, TEM, gravity surveys) and geologic data (results of geologic mapping, age dating, lithologic, mineralogic and fluid inclusion investigations of cuttings and core). These data were collected primarily by Union Oil Co., Phillips Petroleum Co., CalEnergy Co., Calpine Corp. and the USGS. They represent a very significant investment by the geothermal industry. EGI researchers have already obtained the well samples and a significant amount of the chemical and geologic data. This data package represents one of the most complete data sets on a volcanic system ever made available to DOE researchers. Much of this data has been made available exclusively to EGI.

Additional data that bear directly on the development of a Glass Mountain EGS reservoir model will become available during the course of this project as a result of a variety of ongoing and proposed investigations funded by the DOE and other organizations. We will cooperate and communicate frequently with these investigators so that all groups can benefit from the work. Interpretation of geophysical data by Dr. William Cummings and the Calpine Corp. (funded by the California Energy

Commission) will provide data on the structural, permeability, lithologic and mineralogic characteristics of the subsurface rocks. Analyses of aerial/satellite images by Drs. Greg Nash, W. Pickles (LLNL) and E. Silver (USC) submitted under this solicitation will yield information on the distributions and orientations of fractures and faults that extend to the surface. Dr. **Andreas Henk, University of Freiburg, Germany** has agreed to collaborate on finite-element modeling of the stress regime. He has proposed to obtain independent funding for this work through the German Science Fund. Mr. Kevin Bloomfield will conduct numerical simulations to characterize fluid flow within the reservoir rocks. His studies will be funded through the Idaho National Engineering and Environmental Laboratory. The proposed work by Drs J. Moore and D. Norman (proposed under this solicitation) will use mineralogic data generated during this study and fluid analyses to numerically evaluate the effects of mineral sealing and dissolution on fracture permeability.

Statement of Work

Task 1. Data Acquisition and Review

An extensive database already exists on the Glass Mountain area. During the initial phase of this investigation, the team will collect and review the existing data and determine the requirements of individual researchers, including those working on complimentary investigations funded by the DOE, the California Energy Commission, USGS and other organizations. Gaps in the data base will be identified and redundancy will be eliminated.

Task 2. Compilation of Existing Data

The existing well logs and the results of the available geologic, geochemical and geophysical investigations provide considerable information on the characteristics of the subsurface rocks, their permeabilities, temperatures, fluid compositions and hydrothermal alteration. We will compile and synthesize the available data to develop a basic three-dimensional understanding of the subsurface conditions at Glass Mountain. Emphasis will be placed on features that control permeability (e.g. faults and fractures, permeable lithologies, hydraulically conductive zones) and on the characteristics of low permeability areas. The computer program Petrel® (Schlumberger) will be utilized to develop a three dimensional visualization of the data in the region.

The results of this compilation will be used to help select the most appropriate wells for study in Tasks 3-5. New data generated from these investigations will be integrated with this initial synthesis to develop a structural model of Glass Mountain in Task 6.

Task 3. Characterization of the Subsurface Fracture Networks

The characterization of the mechanical, hydrologic and petrologic behavior of the subsurface rocks and of the existing fracture networks represents a major component of the proposed study.

Fracture distributions, geometries and kinematics

The distributions and characteristics of the fractures encountered in the core holes and deep wells will be mapped and described. We will document: fracture abundances, dip azimuth and dip of the fracture walls, fracture/rupture mechanisms (e.g. tensile fracture, strike-slip fault), trend and plunge of slip vectors from fracture-wall shear criteria and opening vectors from fibrous mineral fillings, cross cutting relationships among the fractures, cross cutting relationships among displacement vectors in each individual fracture, the degree, type and sequence of mineral filling, fracture lengths, widths, and apertures. Fractures that are hydraulically conductive will identified from analyses of the pressure-temperature (+/- spinner) logs, lost circulation zones encountered during drilling and drilling breaks. Fault cores and damage zones will be characterized when encountered in the core holes. Lithologies will be mapped to determine the relationship between rock type and fracturing.

The large-scale structural framework of the region will be determined from the results of previous geologic mapping, the currently funded California Energy Commission funded geophysical investigations and the interpretation of satellite images and aerial photographs (proposed by Nash and others under this solicitation). The large-scale structures that are identified using these techniques will be correlated with structures identified in the wells using the three dimensional projection and linkage capabilities of Petrel® (Schlumberger).

Petrologic characteristics of the rocks and fractures

Investigations of natural geothermal systems demonstrate that fluid-mineral interactions play an important role in controlling permeabilities and the rocks' mechanical properties. Rock lithologies and the mineral assemblages observed in the fractures, veins and rock matrix will be described mesoscopically and in thin section. Standard petrographic techniques will be supplemented with X-ray diffraction analyses. X-ray analyses are the best means of estimating mineral abundances and identifying the clay minerals, which have a particularly strong influence on rock behavior. Electron microprobe and scanning electron microscopes are available to further characterize mineral textures and compositions. The mineralogic data will be used to evaluate and predict the rheological properties of the lithologies encountered at depth.

The fractures and veins represent the main permeability channels. We will determine and document the mineral assemblages, paragenetic relationships, and mineral textures to determine the relative age of the fractures, evidence of reactivation and changing stress fields, the characteristics of hydraulically conductive and sealed fractures, the relative direction of fluid movement through them (e.g. downward moving recharge or upward moving discharging fluids) and the effects of mineral sealing and/or formation damage. The mineral assemblages associated with hydraulically conductive fractures will be evaluated with respect to possible geophysical techniques that can be used to trace them.

Although the emphasis of our petrologic investigations will be on the interrelationships between mineralization and fracture development, our experiences suggest that the effects of injection induced and naturally occurring mineral deposition are underrated and that they will be significant in EGS reservoirs. The formation of reservoir cap rocks that become effective seals through mineral deposition demonstrate that rocks with low initial permeabilities are very sensitive to even small changes in their fracture characteristics. Mineral deposition in EGS reservoirs may result from pressure gradients induced by injection and production (which could, for example, cause inflow and deposition of anhydrite and carbonate), mixing of injected and indigenous fluids and injection of flashed fluids supersaturated in silica and other phases. We anticipate it will be possible to mitigate some of these effects by proper injection strategies if information is available on the natural circulation patterns, fluid chemistries, and the minerals accessible to the injected fluids. For example, Calpine Corp. has reported improvements in permeability following acid stimulation of the Telephone Flat wells, although the reasons for this improvement are not known. The petrologic and chemical data developed in this investigation, as it relates to permeability enhancement and degradation, will be considered quantitatively in a separate proposal submitted under this solicitation by Drs. J. Moore and D. Norman.

Porosities in volcanic rocks may vary by orders of magnitude. High initial porosities are frequently associated with breccia zones at the top and base of lava flows, volcaniclastic sediments, cinder deposits, gas cavities, fractures, and cavities formed through dissolution of mineral grains. Although high porosities can enhance the overall volume of an EGS reservoir, their presence may decrease the initial effectiveness of fracture propagation during hydrofracturing. The controls on rock porosities will be considered in developing an EGS reservoir model of Glass Mountain.

Task 4. Determination of In-situ Stresses

Knowledge of the modern stress field is needed to predict which fractures will be reactivated during hydrofracturing. As indicated above, the magnitudes of the stresses can be expected to vary laterally and vertically. No electric imaging logs (FMI or FMS logs) or oriented core are available from Glass Mountain. Consequently it will be necessary to determine the in-situ stresses from the orientations of fault striae and extensional fractures preserved in the core. In this study, we will use the paleomagnetic signature of the core samples to orient the fractures. Principal stress directions and the ratio of their magnitudes will be calculated by stress inversion, using our own programs Cluster and Twing (Nemčok and Lisle, 1995, Nemčok et al., 1999). Other data necessary for stress magnitude calculations such as the vertical stress magnitude and maximum/minimum stress magnitude ratio will be obtained from well logs and rock mechanics tests, respectively (see Nemčok and Gayer, 1996). These ratios and the vertical stress magnitude will allow calculation of the magnitude of all three principal stresses (see Gaviglio, 1985; Angelier, 1989). Available earthquake or GPS data from the region represent an alternative option for stress determinations and will be utilized if available.

Task. 5. Determination of Rock Rheologies

In order to predict the tendency of fractures to reactivate during the injection of hot or cold fluids or during hydrofracturing, the rheologies of the reservoir rocks must be determined. Information is needed on intact and residual rock cohesion, intact and residual angles of internal friction, Young's moduli and Poisson's ratios. These data can be obtained from the results of triaxial stress tests. However, because of funding limitations, it will be necessary to rely on published rock mechanics data.

Task 6. Development of an EGS Reservoir Model of Glass Mountain

Data generated on the fracture, lithologic and mineralogic characteristics of the subsurface rocks in Task 3 will be integrated with the in-situ stress distributions (Task 4) and rock rheologies (Task 5) to refine the initial synthesis conducted under Task 2 and develop a structural model of the Glass Mountain area. The distribution of rock types, structures, rheologies, temperatures and secondary minerals will be illustrated in three dimensions using the Petrel® (Schlumberger) software. Faults penetrated by the wells will be projected and connected to faults mapped at the surface and those based on geophysical and remote sensing data. Fault core and damage zone thicknesses will be portrayed. The depth to the base of the reservoir (brittle/ductile boundary) will be determined and shown. The mapped data will be used to assign fault rheologies.

In situ stress data will be used to analytically calculate shear and normal stresses resolved on mapped faults and fractures and their tendency to slip, dilate or completely close, crushing any remaining asperities and propping breccias. These calculated results will be mapped in three dimensions.

A second model, using a robust finite-element approach will be developed using the software ANSYS® (Ansys Inc., Houston, USA). This model would be developed in collaboration with Dr. Henk who would utilize his own funding for the work. The advantage of this approach is its robustness, which allows calculation of local stress perturbations in various fault blocks and the response to local pore fluid pressure changes introduced either by reservoir depletion or fluid injection. A shear-softening record will be simulated with finite-element models of stress buildup within the reservoir when the boundary conditions, internal properties and surface conditions are determined. Shear softening modeling will be used for predicting the fracture pattern in parts of the reservoir where well data are not available. Fracture distribution models will be constrained by data from the surface and borehole fracture studies, in situ stress data and rock mechanics data. Some wells with data will be "set aside" to validate the results. Both fracture location and fracture reactivation prediction calculations will be performed. One of the most useful aspects of the model is its ability to treat unequal dilation and internal friction angles, which is most appropriate for upper crustal geologic materials in which plastic behavior is combined with pressure-dependent frictional, dilatant behavior. Eight-node isotropic brick elements would be used to describe our models. All nodes would be in communication during each time-step and compatibility, and equilibrium would be achieved by iteration. To simulate geologic process during one stress buildup, each model would be run until failure of the major faults occurs. In the models, bands of localized deformation would be treated as simulating brittle failure. The presence or initiation of localized deformation would not introduce additional discontinuity into the numerical model. All interfaces within the models would be true discontinuities, and these would be created prior to the simulation. All continuous regions would remain continuous throughout the simulation. Pre-existing faults in the numerical model would be identified as "contact elements". This approach would handle large differential movements between parts of the model, but would not describe the fault propagation. The contact element would be defined at opposite surfaces of the pre-assigned fault and would be capable of describing frictional sliding. The contact stiffnesses would be used to enforce compatibility between adjacent fault surfaces. The results of the finite-element modeling will allow tracking the behavior of existing fractures. These results will be represented on maps of incremental and finite strain, dilatancy, principal stresses and differential stress versus rock strength. Strain and dilatancy maps will be used to locate areas of deformation; principal stress and differential stress versus rock strength and will be used to determine the failure mechanism and controlling dynamics. This modeling will constrain the spatial and temporal evolution of failure and deformation, providing fracture intensity maps, determination of fracture timing, mechanism and controlling stress.

Task 7. EGS Reservoir Evaluation

The reservoir models will be used to predict the factors controlling permeability, predict stress field distributions outside the immediate well bore environment and to suggest the most likely sites for future EGS development. The results of Dr. Henk's models will be used to numerically predict stress distributions and fracture orientations in areas without well data. The validity of these models will be tested by comparing the predicted results with fracture characteristics in selected core holes that were "set aside" before the numerical modeling is conducted.

Project Management Plan

Figure XX shows the project tasks and milestones. The work will be conducted over a three year period. There are two major targets. The first is the development of an EGS reservoir model and the second is reservoir evaluation. These targets can be achieved with the samples and data already available at EGI. Thus we do not see any difficulties in reaching the projects objectives.

Project Management Structure

The Principal Investigator, Dr. Joseph Moore, will be responsible for the overall management of the project and coordination of the tasks among the researchers. He will maintain close contact with the researchers so that the scheduling of the research activities proceeds in a logical manner. The activities will be monitored through quarterly reports prepared by the researchers, and when necessary, more frequently through conference calls and electronic mail. Important petrologic and structural observations will be documented photographically so that other qualified investigators can review them. The quarterly reports will be reviewed and compiled by the Principal Investigator to ensure that progress is consistent with established milestones and the objectives. He will report significant deviations from the proposed research program to the Program Administrator.

At the conclusion of each year, the Principal Investigator will review the progress of the research with the Program Administrator for the purpose of reestablishing or modifying, if necessary, task priorities for the coming year.

Management Philosophy

We clearly understand that the purpose of this project is to provide new techniques and tools to the U.S. geothermal industry so that it can reduce the inherent costs and risks of developing EGS reservoirs. Consequently we sought to assemble a team that is highly qualified, interdisciplinary, well respected by the industry, and committed to scientific excellence.

We will maintain close contact with the industry and DOE program managers throughout the course of the project. By working cooperatively with industry personnel, we will insure that they are kept aware of our progress and results. These results will be clearly documented and scientifically defensible.
We recognize the need to complete our tasks on time and within budget. The Principal Investigator will monitor costs and progress on the proposed milestones will be carefully tracked as discussed above. The project will be managed in accordance with the policy and procedures established by the University of Utah for the conduct of the faculty and staff.

Reporting

Quarterly and yearly reports prepared by the researchers will be compiled and submitted to the Program Administrator by the Principal Investigator. These reports will also be distributed to the project team. Reports to the geothermal and scientific community will be prepared according to the proposed milestones. At the conclusion of this project, a final report will be prepared and submitted to the Program Administrator.

Project Team

The key personnel on this project will be Dr. Joseph Moore, Mr. Jeffrey Hulen and Dr. Michal Nemčok. Dr. Moore will serve as Principal Investigator. Mr. Hulen and Dr. Michal Nemčok will act as Co-Principal Investigators.

Dr. Moore will oversee work on the project and coordinate communication and reporting activities. He will conduct petrologic, lithologic and geologic studies with an emphasis on the core holes. Dr. Moore will be responsible for the interpretation and synthesis of available geochemical (rocks, fluids and soils) and fluid-inclusion data and will conduct additional petrologic investigations (e.g. fluid inclusion, scanning electron microscope, electron microprobe analyses) as needed.

Mr. Hulen will conduct mineralogic, lithologic, and geologic investigations. His primary focus will be on samples from the deep wells. Mr. Hulen will be responsible for interpretation of the X-ray diffraction analyses and for synthesizing the temperature and mineralogic data.

Dr. Nemčok will take the lead in developing the structural model of the Glass Mountain area. He will be responsible for defining, modeling and predicting stress distributions and magnitudes, rock properties and fracture characteristics and geometries. He will provide guidance to graduate students assisting in the structural aspects of this project.

Related Experience of Team Members

The research team assembled for this project is highly qualified. All of the researchers have conducted investigations in their respective fields on volcanic-hosted geothermal systems and, as a group, the team has a long history of successful collaboration on geothermal projects involving diverse topical studies. An abbreviated resume, highlighting the experiences of the key researchers is attached to the end of this document. The following is a summary of the related expertise of the individuals who will be contributing to this project.

Dr. Joseph N. Moore (EGI) has been actively involved in the study of geothermal systems since the mid 1970's. His research has focused on the chemical and thermal structure of geothermal systems and the application of fluid inclusions to understanding their evolutions. Dr. Moore has worked on numerous volcanic-hosted systems including Awibengkok, Indonesia, Bulalo, (Philippines), Karaha-Telaga Bodas (Indonesia), Los Azufres (Mexico) Mt. Meager (Canada), Glass Mountain (California), Tiwi (Philippines) and Zunil (Guatemala). He has worked extensively within the U.S, most recently at Coso, Cove Fort, Salton Sea and The Geysers. Dr. Moore has served as a consultant to the U.S. DOE, private exploration and development companies, international agencies, and foreign governments. He is currently Associate Editor for the Americas of the journal Geothermics.

Mr. Jeffrey Hulen (EGI) is a geologist specializing in the hydrothermal alteration of geothermal systems. He is served as Chief Scientist on the DOE sponsored Awibengkok, Indonesia project. Mr. Hulen previously served in this capacity on Continental Scientific Drilling projects in the Valles caldera (VC-2A, 1986; VC-2B, 1988), the USGS-NSF-DOE-sponsored Creede scientific drilling project (1991), and the DOE-Unocal Corporation-cosponsored Geysers Coring Project (1994). Mr. Hulen has conducted detailed mineralogic and petrologic studies on Awibengkok (Indonesia), and in the U.S. at Coso, The Geysers, the Salton Sea and the Valles Caldera.

Dr. Michal Nemčok (EGI) is a structural geologist whose career has focused on large-scale tectonic model development and detailed fracture stress studies. He has worked in a variety of volcanic-hosted fossil and active hydrothermal systems, including the Mid-Slovakian Volcanic Field in the Slovak Republic and the geothermal system at Karaha-Telaga Bodas, Indonesia. In addition, he has worked at Coso, the Salton Sea and the Long Valley Caldera. Dr. Nemčok has led or co-authored the design of three computer programs on stress inversion from polyphase fault/slip data, developed numerous fracture analysis programs, and has collaborated in the modification of finite-element techniques developed for stress, strain and fracture predictions. Dr. Nemčok has applied these methods in extensional, strike-slip and thrustbelt settings. He has coauthored a structural geology textbook.

Equipment, Facilities and Other Resources

Facilities housed at EGI that will be utilized during this project include the EGI Geothermal Sample Library, an X-ray diffraction laboratory, a fluid-inclusion laboratory and petrographic microscopes equipped with cameras for documenting important relationships. The Geothermal Sample Library has more than 1500 m^2 (17,100 ft^2) of floor space for sample storage, and currently houses more than 177,000 m of geothermal cuttings, and more than 110,000 m core from geothermal systems throughout the world. The X-ray diffraction laboratory houses a Philips X-ray diffractometer and facilities for preparing X-ray diffraction powder mounts and doubly polished mineral plates for fluid-inclusion studies. The fluid-inclusion laboratory contains Linkam and Fluid Inc. heating and freezing stages with dedicated microscopes, cameras and computers. Scanning electron microscopes (SEM) and electron microprobes are available nearby on the campus of the University of Utah.

A variety of computer programs is available in house for the interpretation of structural and rock mechanics data. These programs will be used to calculate the stress regime from the fracture data, fracture slip and dilation tendencies under modern stress regime and their ability to preserve residual permeability. The program 2Dmove® (Midland Valley) will be used for construction of area-balanced cross sections, used as elements for the three dimensional model development. The computer program Petrel® (Schlumberger), will be used to develop a three dimensional visualization of the Glass Mountain area. Both programs will be provided as part of the overall cost share to the project.

Technology Transfer

The primary client for our research is the U.S. geothermal industry. The results of our work will be transferred to the industry in several ways. We will maintain close contact with our industry partner. We will periodically present our findings at annual Geothermal Resources Council conferences, Stanford Reservoir Engineering Workshops, and DOE geothermal program reviews so that the industry will be able to utilize and test our results as they become available. EGI researchers have an excellent reputation for presenting results in a timely fashion. In addition, those results considered to be of interest to broader audiences will be presented at selected scientific conferences, such as the American Geophysical Union, Geological Society of America meetings and in peer reviewed journals.

No barriers to the dissemination of the studies results are anticipated.

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Biographical Sketch

Joseph N. Moore

EDUCATION:

B.S., Geology, 1969, City College of New York
M.S., Geology, 1972, Pennsylvania State University
Ph.D., Geology, 1975, Pennsylvania State University

PROFESSIONAL POSITIONS:

1995-Present	Research Professor/Senior Geologist, Energy and Geosciences Institute, Department of Civil and Environmental Engineering, University of Utah: Conduct research on the hydrothermal alteration and thermal and chemical structure of geothermal resources. Prepare proposals and perform research for government, private and academic institutions. Present workshops on geothermal exploration, geology and geochemistry.
1979-1995	Geologist/Section Manager/Project Manager, Geochemistry Group, University of Utah Research Institute: Conduct geologic and geochemical studies of geothermal systems; Overall responsibility of geochemical laboratory and supervision of chemists and geochemists involved in the analysis and research of geothermal waters, minerals, and rocks for DOE, private and academic institutions.
1975-1977	Staff Geologist, Uranium Division/The Anaconda Company: Conduct exploration for hydrothermal uranium deposits in the western U.S.

PUBLICATIONS

Allis, R. and Moore, J., 2000, Evolution of volcano-hosted vapor-dominated geothermal systems: Transactions, Geothermal Resources Council, v. 24, p. 211-216.

Moore, J. N., Christensen, B., Browne, P. R. L. and Lutz, S. J., 2004, The mineralogic consequences and behavior of descending acid-sulfate waters: an example from the Karaha-Telaga Bodas geothermal system, Indonesia: Canadian Mineralogist, in press.

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ACTIVITIES:

2001-Present	Board of Directors, Geothermal Resources Council; currently serving second term
1999-Present	Associate Editor for the Americas of the journal Geothermics

Michal Nemčok

EDUCATION

1991
Ph.D. dissertation, Comenius University Bratislava, Czechoslovakia
Title: The Cenozoic Development of Western Half of the West Carpathian Orogenic Belt (in Slovak).
undergraduate work, Comenius University Bratislava, Czechoslovakia: structural geology, sedimentology, paleontology, ore-analysis, geochemistry, petrology, mineralogy, programming, stratigraphy, economic geology, tectonics.
2002
"Venia docendi" in Geology, University of Freiberg, Germany (May 21, 2002). Thesis title: "Paleostress methods and development of the Carpathian orogenic belt" (in German).

PROFESSIONAL POSITIONS

1998-present	Research Professor/Research Assistant Professor, Energy and Geosciences Institute, Department of Civil and Environmental Engineering, University of Utah
1997-1998	Alexander von Humboldt Fellow at University of Würzburg, Germany
1996-1998	Head of Hydrocarbon Exploration Department at Slovak Geological Survey

PUBLICATIONS

Nemčok, M. and Gayer, R. A., 1996, Modelling palaeostress magnitude and age in extensional basins: A case study from the Mesozoic Bristol Channel basin, UK: Journal of Structural Geology, v. 18, p. 1301-1314.

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ACTIVITIES:

Presenter, Short Course, Thrustbelts: Structural architecture, thermal regimes, and petroleum systems, AAPG Annual Meeting, June, Salt Lake City, 2003
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U of U student funding - 20k per year
Andreas Henk, co-operator in numerical stress and fracture prediction going for his own federal German funding (I would anticipate several k per year).