PROCEEDINGS, Twenty-Eighth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 27-29, 2003
SGP-TR-173

^{40}AR/^{39}AR THERMAL HISTORY OF THE COSO GEOTHERMAL FIELD

Lynne Kurilovitch, Dave Norman, Matt Heizler, New Mexico Tech; Joe Moore, EGI, University of Utah, Salt Lake City, Utah, Jess McCulloch, Caithness Operating Company, Reno, Nevada

New Mexico Tech
E & ES, 801 Leroy Pl.
Socorro, New Mexico, USA
e-mail: lynnek@nmt.edu; dnorman@nmt.edu; matt@nmt.edu; jmoore@egi.utah.edu, jmcculloch@caithnessenergy.com.

ABSTRACT

The age of the geothermal system and the granitic host rock at Coso geothermal system in California is poorly known. This is mainly due to a paucity of vein-type minerals (e.g. adularia, sericite) that can be directly dated. A downhole ^{40}Ar/^{39}Ar thermochronology study of granitic host-rock K-feldspar is presently being undertaken at the New Mexico Geochronology Research Laboratory at New Mexico Tech. The technique couples the measurement of argon loss from K-feldspar and knowledge of the diffusion parameters of transport in K-feldspar to estimate the longevity of the system at present day temperature and also to obtain an estimate of the host rock age. The study centers around a vertical distribution of samples obtained from Coso well 73-19 that reaches temperatures of 325^{o}C at a depth of 1550m and thus represents one of the hottest producing wells in the Coso system. Four samples from Coso well 73-19, from depths 550m (downhole temperature 150^{o}C), 700m (200^{o}C), 1085m (275^{o}C), and 1850m (325^{o}C), were isolated from the granitic host rock chip samples. These samples were analyzed by the ^{40}Ar/^{39}Ar age spectrum method where the data recorded significant and variable degrees of argon loss due to the range and magnitude of the present day temperatures sampled. The amount of argon loss from the samples analyzed increases as expected as depth and temperature increase downhole, yielding integrated ages that decrease with depth, but initial steps do not reach 0 apparent age. Lovera et al's (1989) Multi Diffusion Domain method was used to compare thermal history models with measured data. The modeling supports a duration for the Coso geothermal system of definitely less than 100 ka, and possibly as short as 10 ka. This is much younger (< 100 ka vs. < 300 ka) than previous age estimates for the Coso geothermal system. Additional thermochronological sampling at Coso is planned to test the validity of these preliminary results.

INTRODUCTION

The Coso geothermal field is located in southeastern California on the western edge of the Basin & Range Province. Coso is a high temperature geothermal system that produces approximately 240 megawatts of electricity. The host is Mesozoic granitic intrusive rock. These rocks have undergone low-grade propylitic alteration from the geothermal fluids, but they show little hydrothermal vein mineralization. A lack of potassium-bearing vein minerals has prevented the system at Coso from being dated effectively in the past. Yet there is much interest in the age and thermal history of this system. This study uses an indirect method, the Multiple Diffusion Domain model, to provide thermal history models for the Coso system. For this type of thermochronology study, it is necessary to have K-feldspar samples from several depths in one well that also has temperature data. One of the known producing wells near the center of the system, Coso well 73-19 (near

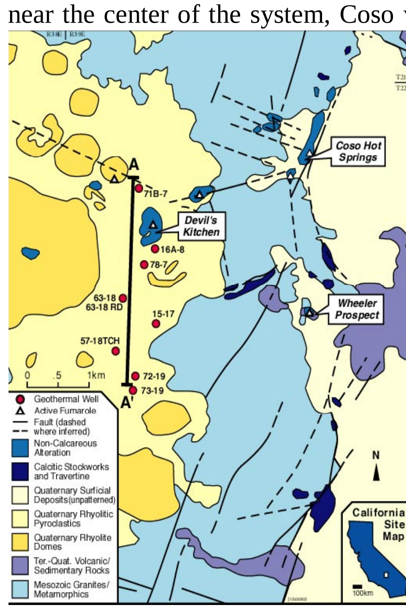


Figure 1. Geologic map of Coso geothermal field, inset shows location in state of California, USA

the A' in figure 1), was chosen for this project. This well was chosen because the chip samples were available, fluid inclusion temperature data was available, the temperatures go above 300ºC, it is granitic through most of its depth, it is a producing well, and it penetrates the main plume of the geothermal system. Chip samples from four depths in well 73-19 were chosen for this study. They are

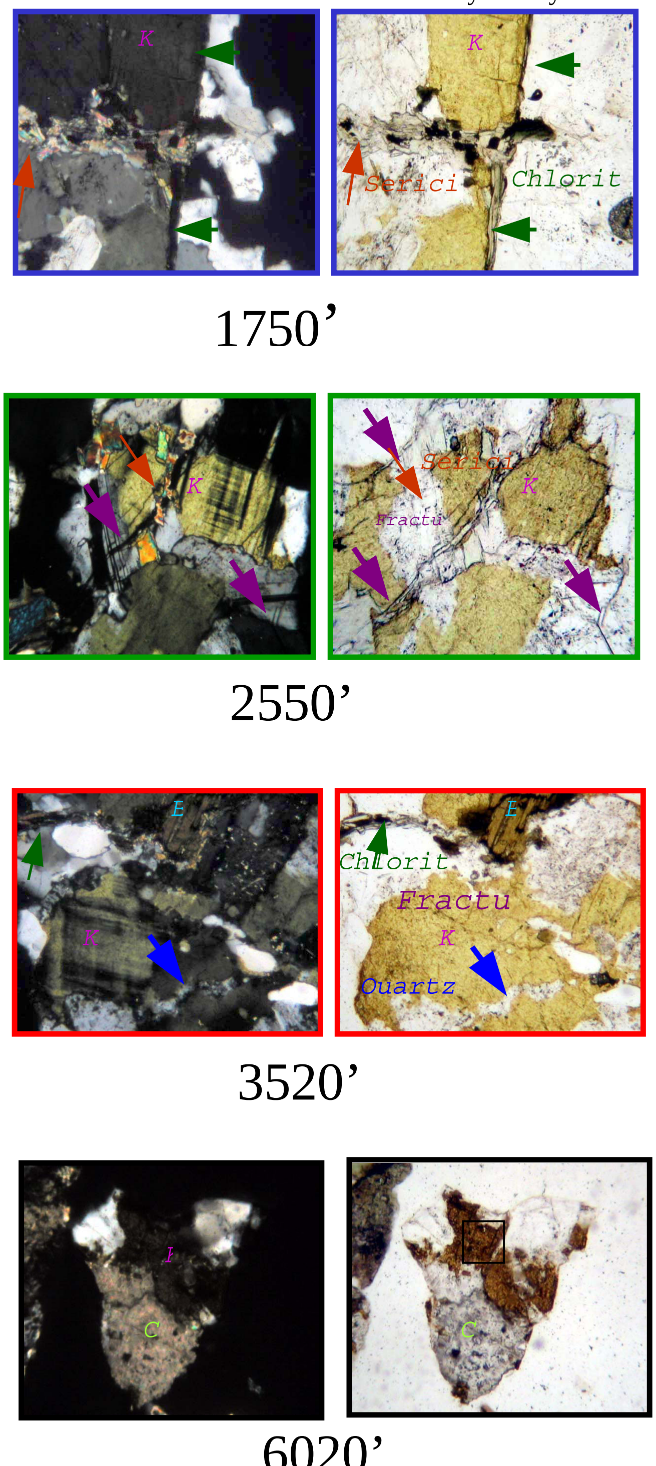


Figure 1. Photomicrographs of thin sections of chip samples used for study. Left side is in polarized light, right side is same view in unpolarized light. Arrows indicate fractures or veins. K= K-feldspar, C = calcite, B = biotite. All are 12X except 6020' = 17X.

the 1750', 2250', 3520', and 6020' samples. The total depth of well 73-19 is just over 6000'. These samples are granitic and all contain K-feldspar (see figure 2).

The purpose of this project is to determine the age of the current geothermal system at Coso, how long the system has been at its present temperatures, and the stage of development of this system. The system could be heating up as a young system would, cooling down as an older system would, or somewhere in between. This information is of interest both to those concerned with the economics of producing from this field and others like it, as well as to the scientific community.

GEOCHRONOLOGY AT COSO

The high temperature system present today is one of three possible episodes of geothermic activity that have been previously recognized at Coso (Adams et al., 2000). The age determinations that have been made at Coso in the past have been on surface deposits – recent volcanics, surface sinter or travertine. The sinter (indicates a moderate- to high-temperature system, >225ºC) has been dated at 238 ka by using datable interbedded basalt flows, and the travertine (indicates a low- to moderate-temperature system <225ºC) at 308 ka using U/Th (Adams et al., 2000). The current high temperature system (>300ºC) has not been dated because there has been no K-bearing vein mineralization (such as adularia or alunite) produced by this system. These minerals can be dated directly, and that is the way many geothermal systems are dated when they are present.

If a high- or even moderate-temperature geothermal system had been active since the sinter was being deposited over 300 ka, there would be evidence of much more extensive hydrothermal alteration and mineralization at Coso. Hence, the present geothermal system is not only younger, but may be much younger than 300 ka.

There is another way to at least approximate the age of geothermal systems when the host rock has K-bearing minerals, such as the granitic wall rock at Coso. Some of the properties specific to K-feldspar that make it poorly suited for conventional K-Ar age dating makes it desirable for $^{40}Ar/^{39}Ar$ dating. The age spectrum technique uses a step-heating process to release argon incrementally, thus producing data from which thermal histories can be modeled via the Multiple Diffusion Domain (MDD) method (Lovera et al., 1989). This method models K-feldspar crystals as containing discrete diffusion domains of varying size. All the domains have the same diffusivity and activation energy, but the smaller diffusion domains release argon more readily and at a lower temperature than the larger domains, as there is a shorter distance for the argon to travel. The domains are considered to be separated by physical boundaries within the crystals. These boundaries may be cleavage planes, twinning lamellae, fractures, perthite lamellae, grain boundaries, etc. For the models presented here, we assume slab-shaped diffusion geometry, however this choice is not critical to model results.

The step heating process used for the $^{40}Ar/^{39}Ar$ analysis of K-feldspar degasses the argon dependent upon the diffusion domain distribution (McDougall & Harrison, 1999). The degree of argon loss is dependent on the temperature the crystal is subjected to as well as the length of time it is exposed to that temperature. For multi-domain samples, the smallest diffusion domains will be degassed to a higher degree than larger domains and thus the resulting shape of the measured age spectrum will be a function of the domain distribution and the thermal history. The age spectrum can then be modeled to estimate the thermal history of the geothermal system.

The step heating of minerals from rapidly cooled rocks like volcanics yield flat age spectra (like the top spectra in figure 3) because they have not undergone complex thermal histories. The age spectra resulting from the step heating of K-feldspar with multiple diffusion domains are complex due to the complex thermal histories expected from samples in a geothermal system. These samples typically form a spectra rising from left to right in a stair-step fashion (see middle two spectra in figure 3). With knowledge of past temperatures obtained from fluid inclusions and/or present day downhole temperatures, the longevity of the geothermal system can be estimated by modeling these complex K-feldspar age spectra.

The shape of the age spectra that result from rapidly cooled rock like volcanics containing sanidine (a high temperature form of K-feldspar) tend to have a relatively flat spectrum like shown in figure 3a. This is because the sanidine essentially closes to argon loss immediately following eruption. K-feldspar crystals in granitic rocks are microstructurally complex and therefore contain many diffusion domains. During heating of the K-feldspar within the geothermal system, the smallest diffusion domains are degassed first with partial to complete degassing of more retentive domains depending upon the intensity and duration of the thermal history. The argon concentration within the K-feldspars can be mapped out with the age spectrum and is shown diagrammatically in Figures 3b and 3c. The stair step pattern of the age spectrum mimics the argon concentration and thus mimics the degree of argon lost during heating in the geothermal system. The difference between spectra 3b and 3c is the length of time the sample would have been reheated – longer time at the same temperature would shift the spectra down on the right end because more argon loss would have occurred, and the spectra would more closely approach the 0 age that would result from total resetting. Complete present day resetting would yield a zero-aged flat spectrum (Fig. 3d).

A suite of K-feldspar bearing samples from a range of depths and temperatures can be used to study the thermal history of a geothermal system. This requires knowledge of the present day temperatures. Downhole temperatures may be used, or fluid inclusion temperatures may be used if they are close enough to the present day temperatures. Fluid inclusion temperatures (Moore, 2002, personal communication) were used in the initial thermal history modeling for this project.

ANALYTICAL METHODS AND PROCEDURES

$^{40}Ar/^{39}Ar$ dating was performed at the New Mexico Geochronology Research Laboratory (NMGRL) at New Mexico Tech in Socorro, New Mexico. The four granitic samples from the Coso 73-19 well used for this study are from depths of 1750’, 2550’, 3520’ and 6020’. K-feldspar crystals were separated from chip samples with standard heavy liquid, magnetic and handpicking techniques.

Approximately 10 mg of K-feldspar was separated from each sample by hand picking under a binocular microscope, except for the 6020’ sample, for which only ~2 mg were obtainable. The chips from this deepest sample were very fine-grained and this sample had <10% K-feldspar which was tightly intergrown with the other minerals and partially replaced by calcite, so it was very difficult to separate. The other four samples, plus Fish Canyon Tuff sanidine samples, were sent to the reactor at McMaster University in Canada, and irradiated for four hours.

The Fish Canyon sanidine (age 27.84 Ma) was used as the flux monitor for the irradiation. After irradiation these monitor crystals were placed in copper planchets and fused using a CO_2 laser system. J-factors were determined to 0.1% (2-sigma precision) by analyzing four sanidine single crystal aliquots from each of six radial positions around the irradiation vessel.

The four K-feldspar samples from 73-19 were step heated in a double-vacuum Molybdenum furnace. The heating times ranged from 10 to 500 minutes at temperatures from 450ºC to 1750ºC. Argon isotope compositions were determined using an MAP 215-50 mass spectrometer operated in electron multiplier mode with an overall sensitivity of ~2 x 10^{-16} mol/pA. Extraction system and mass spectrometer

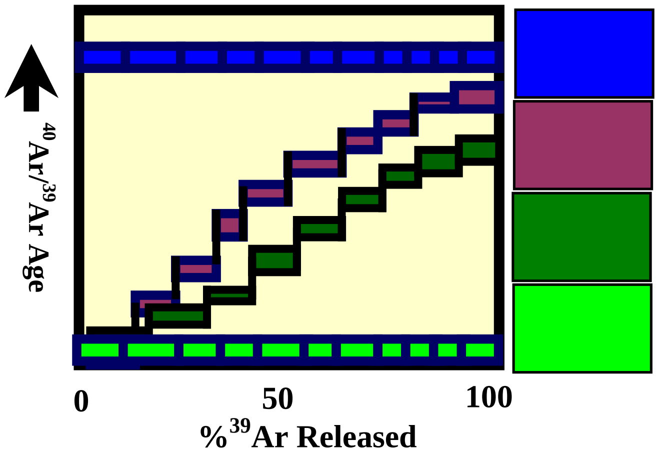
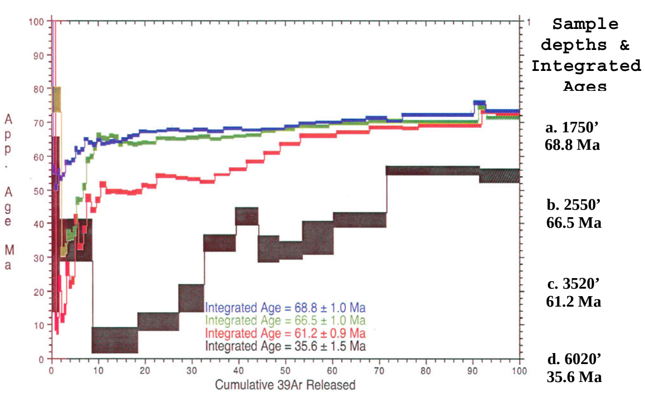


Figure 3. Idealized age spectra: A. Rapidly cooled volcanic rock; B. Slowly cooled granite that has been subjected to reheating by a geothermal system for a short time, causing partial reset of clock; C. After being subjected to the same reheating but for a longer time period. The spectra shifts down on the right side due to the larger amount of argon loss over the greater time D. A flat spectra at 0 apparent age would result from total resestting due to either long exposure or high enough temperature.

blanks and backgrounds were measured prior to analyses. They are: 300 x 10^{-18} moles at mass 40, 2 x 10^{-18} moles at mass 39, 0.5 x 10^{-18} moles at mass 38, 2 x 10^{-18} moles at mass 37, and 2 x 10^{-18} moles at mass 36. The blanks were measured while the furnace was cold or during cooling between heating steps. K-glass and CaF_2 were used to determine interfering reaction correction factors: These are:

$(^{40}Ar/^{39}Ar)_K = 0.0296 \pm 0.00050$
$(^{36}Ar/^{37}Ar)_{Ca} = 0.00027 \pm 0.000005$
$(^{39}Ar/^{37}Ar)_{Ca} = 0.00070 \pm 0.00002$

The integrated ages and errors for the K-feldspar samples are determined by combining all isotopic measurements following the step heating procedure. The decay constants and isotopic abundances used



are those suggested by Steiger and Jager (1977).

The thermal history models were calculated using the multiple diffusion domain (MDD) method of Lovera et al. (1989). Fluid inclusion homogenization temperatures (Moore, personal communication, 2002) were used for the thermal history modeling. These temperatures are:
1750'=145°C, 2550'=225°C, 3520'=275°C, and 6020'=325°C. The activation energy (E) used for the modeling is 42 kcal/mol. This E was chosen from the slope of the initial diffusion coefficients from the Arrhenius plot.

INTERPRETATIONS

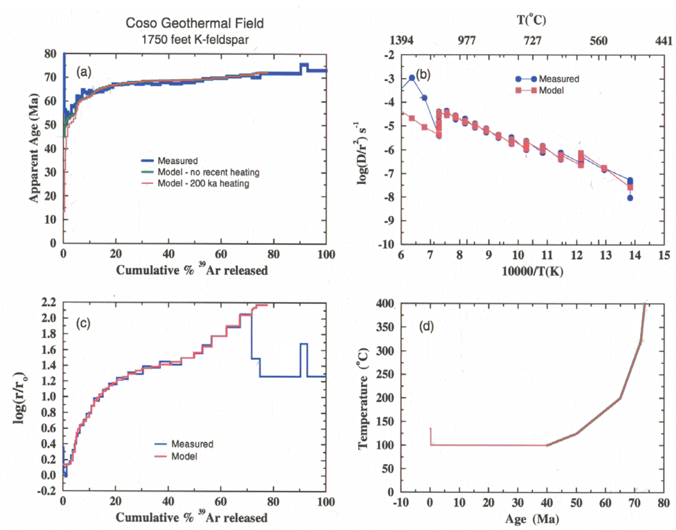
The results of the $^{40}Ar/^{39}Ar$ analysis are presented as individual spectra (Figure 4). Apparent age is plotted on the Y-axis and cumulative % ^{39}Ar released on the X-axis. Each of the heating steps are represented by horizontal line segments that together form stair-step age plots that record present day argon loss (figure 4). The initial high apparent ages (black arrow figure 4) are interpreted to be caused by the release of excess argon.

The calculated integrated ages are indicated under the spectra near the bottom of the graph in figure 4. These integrated ages have no specific chronological significance but decrease with increasing depth (temperature) reflecting higher degrees of argon loss. The minimum age for the host rocks is recorded by the maximum age measured by the age spectra and thus the host rocks are at least 73 Ma. As samples get deeper and hotter the spectra record more bulk argon loss, however apparent excess argon prevents the initial age spectrum steps from recording a zero age that is predicted by present day argon loss. Considering that the high present day temperatures from the Coso system would significantly degas argon from the K-feldspars given enough time, we can estimate a relatively short duration system by simply recognizing that the measured age spectra are not completely reset (Fig. 4). More complete thermal history modeling is now presented to estimate how long the system could have been at the present day temperatures to cause the amount of argon loss measured for the Coso samples.

THERMAL HISTORY MODELING

The Multiple Diffusion Domain (MDD) calculation methods of Lovera et al. (1989) were used to model the thermal history for the Coso samples. Arrhenius plots for each sample were constructed by plotting calculated diffusion coefficients versus the laboratory heating temperature for each heating step.

The Arrhenius plots resulting from the step heating experiments depend on the diffusion domains relative sizes and volume fractions, as well as the duration and temperature of the heating steps used. So the



resulting Arrhenius plot is dependent on the heating schedule used. For samples from 1750', 2250', and 3520' 42 heating steps were used as compared to only 13 steps for 6020' due to its small sample size. The Arrhenius plots do not define ideal initial linear

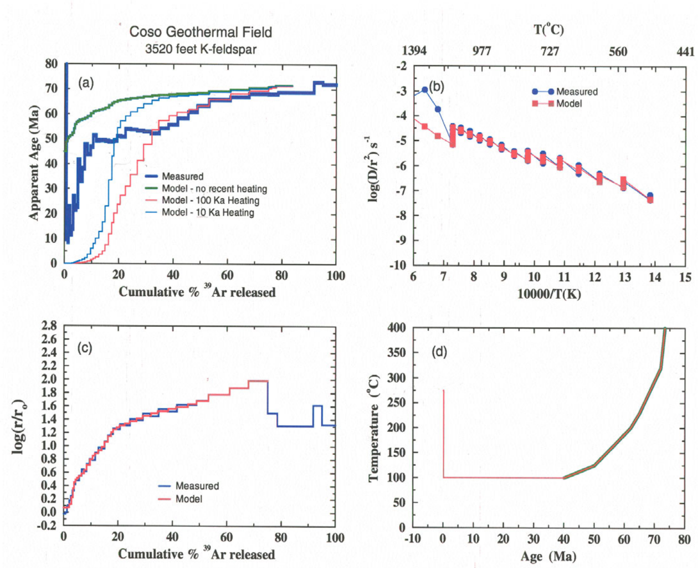
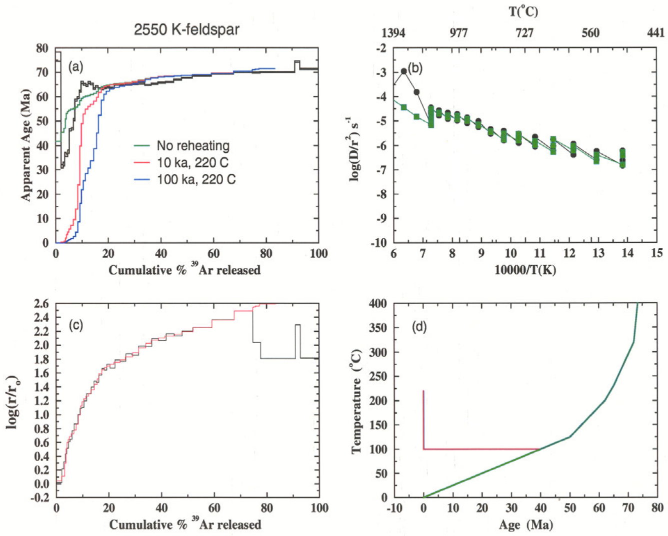


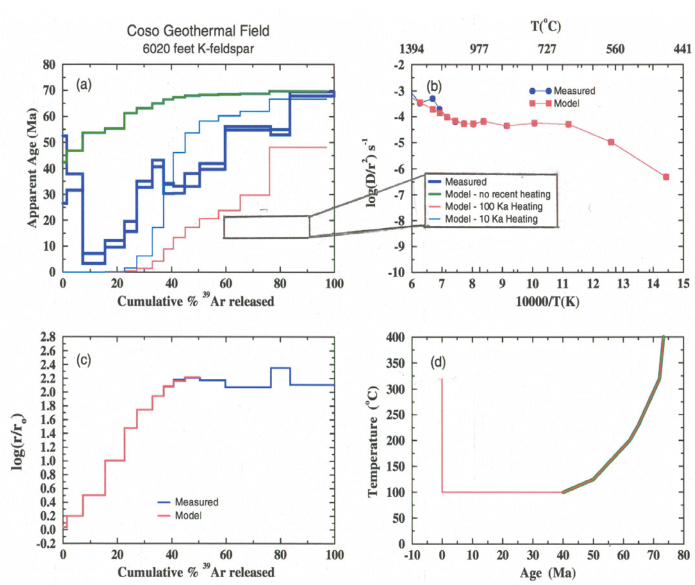
Figure 7. Composite diagram showing thermal modeling results for sample 3520' with reheating at 100 ka or 10 ka. (a) Apparent age spectra, blue line= measured spectrum, green line=with no reheating, red line with reheating to (275ºC) at 100ka, lt. blue line with reheating to (275ºC) at 10ka; (b) Arrhenius plot, blue = measured. red = modeled; (c) Log r/ro plot = difference between measured and modeled Arrhenius data; (d) Thermal model showing temperatures used in red.

segments and thus we can only tentatively assign an E of 42 kcal/mol to each sample for modeling purposes. Using a higher E would yield longer duration estimates for the geothermal system.

The stepped nature of the Arrhenius plots (see figs.



5b-8b) is due to the presence of multiple diffusion domain sizes – a single size diffusion domain sample would yield a single straight-line relationship on the Arrhenius plot. The disintegration of the curve at the left end of the Arrhenius and the right end of the log



r/r_o plots (the r/r_o values are derived from the difference between the measured Arrhenius data and the modeled Arrhenius data) is due to the melting of the K-feldspar at that temperature.

Applying the estimated activation energy (42 kcal/mol) to the fraction of argon degassed from each heating step allows for the calculation of the diffusion domain distribution. The age spectra are then forward modeled using the fluid inclusion temperatures for each sample position.

The temperature history used for the thermal modeling was the same for all four samples from 73-40 Ma. This thermal history is determined from the shallow sample (1750') that apparently has not undergone recent argon loss. Two models describing the more recent history are used for each of the deeper samples. One model assumes a 10 ka heating duration and the other a 100 ka duration. The shorter duration models overall yield better fits between model spectra and measured spectra (Figs. 5a-8a). The 100 ka duration models predict too much argon loss relative to the samples residing at their fluid inclusion temperatures. None of the thermal history models provide excellent fits to the measured data and seem to indicate an overall poor match between the laboratory derived kinetic data and the degree of argon loss resultant from heating in the geothermal system. The model spectra do serve to display that these K-feldspars would be expected to be significantly degassed for heating durations as short as 10 ka, and would be severely affected by 100 ka durations. Perhaps the overall poor fits could be related to some sample alteration or poor resolution of the activation energy. Further work on these and other samples is clearly required to more confidently determine the thermal history, but we do not feel that our major conclusion regarding an overall short duration (less than 100 ka or as little as 10 ka) for the Coso Geothermal field will change significantly.

Another well from the Coso system that reached >300ºC that is adjacent to 73-19 is now being examined by thin section to determine if it contains more K-feldspar that can be analyzed. If it does, similar dating and thermal modeling of another suite of samples from that well will be planned for the near future. Detailed petrographic examination of alteration and mineralization will also be used to interpret the thermal history of the Coso system.

CONCLUSIONS

The suite of four Coso K-feldspar samples analyzed by $^{40}Ar/^{39}Ar$ step heating methods yields progressively younger apparent ages with depth (temperature) as is expected from a sequence of samples from a geothermal well. The most shallow sample (1750') does not record measurable recent argon loss and is consistent with its relatively cool present day temperature and argon kinetic parameters. The hotter samples have all experienced recent argon loss and are used to estimate a 10 ka to 100 ka duration for the present day temperatures.

In all cases for the deeper three samples, a 100 ka duration would cause substantially more argon loss than measured and even a 10 ka duration may be too long. Due to poor fits between measured and modeled data we cannot be more specific regarding the age of the Coso system, however it appears to be significantly younger than previous estimates and appears to be prograding.

More thermochronology data is needed to support a duration of 10 ka or less for the Coso geothermal system. Detailed petrographic descriptions will also facilitate the interpretation of the thermal history of the Coso system.

ACKNOWLEDGEMENTS

This project required much help, instruction, and patience from Lisa Peters and Rich Esser at the New Mexico Geochronology Research Lab. We are very grateful for all their assistance. The Coso chip samples for this study were supplied by Caithness Energy.

REFERENCES

Adams, M. C., Moore, J. N., Bjornstadt, and Norman, D. I., 2000, Geologic history of the Coso geothermal system: Transactions, Geothermal Resources council, V. 24, p. 205-209.

Duffield, W. A., Bacon, C. R., & Dalrymple, G. B., 1985, Late Cenozoic Volcanism geochronology, and structure of the Coso Range, Inyo County, California, Journal of Geophysical Research, 85, no. B5, (19800510), P. 2381-2404.

Heizler, Matthew T. Lux, Daniel R., and Becker, Edward R., 1988, The age sand cooling history of the Chain of Ponds and Big Island Pond Plutons and the Spider Lake Granite, West-central Main and Quebec, American Journal of Science, Vol. 288, p. 925-952.

Lovera, O. M., Richter, F. M., and Harrison, T. M., 1989, $^{40}Ar/^{39}Ar$ thermochronometry for slowly cooled samples having a distribution of diffusion domain sizes, Journal of Geophysical Research, Vol. 94, p. 17,971-17,935.

Lovera, O. M., Richter, F. M., and Harrison, T. M., 1991, Diffusion domains determined by ^{39}Ar release step-heating, Journal of Geophysical Research, Vol. 96, p.2057-2069.

Lutz, S. J., Moore, J. N., Adams, M. C., and Norman, D. I., 1999, Tracing fluid sources in the Coso geothermal system using fluid chemistry, 24th Workshop on Geothermal Reservoir Engineering, Stanford University, p. 188-195.

McDougall, Ian, and Harrison, T. Mark, 1999, Geochronology and thermochronology by the $^{40}Ar/^{39}Ar$ Method, Oxford University Press, 269 p.

Moore, Joseph N., Powell, Thomas S., Heizler, Matthew T., and Norman, David I., 2000, Mineralization and Hydrothermal History of the Tiwi Geothermal System, Philippines, Economic Geology, Vol. 95, p. 1001-1023.