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Abstract

In our first year of the current funding cycle, we have investigated three interrelated aspects of K-feldspar thermochronology; 1) the Ar diffusion properties and microstructures of K-feldspars, 2) the thermal evolution of the Valles Caldera and 3) the continued development of microanalysis.

Results of TEM and light microscopy on heated and unheated samples of MH-10 K-feldspar reveal three classes of substructure are present; (1) cross hatched extinction is common and there is almost no albite/pericline twinning, only tweed microstructure; (2) 5-10 vol. % of this K-feldspar are turbid zones with complex twin and tweed structures at the sub-micron scale and numerous dislocation and strain features; (3) about 20% of the K-feldspar is comprised of 0.01 x 0.2-1 μm albite exsolution lamellae. The network of fractured/turbid zones divides the sample into blocks of approximately 50 μm and the separation between albite exsolution lamellae produce K-feldspar domains of the order 0.1 μm. Independent crushing and diffusion experiments suggest the scale of the largest domain is order ten's of micron whereas the smallest domain size is inferred to be ~0.1 μm. Although this apparent agreement is promising, several inconsistencies remain that will be addressed in the coming year.

Many, and perhaps most, alkali feldspars contain diffusion domains with activation energies that may vary by as much as 8 kcal/mol. An extraordinary consequence of even relatively small variations in activation energy between domains is that the shape of an age spectrum can change dramatically by varying the laboratory heating schedule. We find that Arrhenius and $\log(r/r_0)$ plots have the potential to reveal even small differences in activation energy (~2 kcal/mol) between domains, at least in cases where the domains are well separated in size. Variations in activation energy of ~5 kcal/mol can result in differences in calculated closure temperature of up to 30°C from that obtained assuming equal activation energies for all domains.

We have performed $^{40}Ar/^{39}Ar$ age spectrum experiments on K-feldspar separated from Proterozoic quartz monzonite taken from a depth of 1.76 km down the VC-2B drill hole, Valles Caldera, north-central New Mexico. Our results reveal a classic diffusion domain structure but virtually no recent degassing of radiogenic argon, despite the present temperature of 295°C. These results suggest that near peak temperatures in the Sulphur Springs hydrothermal system have only been achieved over the past 10,000 years. This result is similar to our earlier finding from the Hot-Dry-Rock site but contrast with our previous result from Baca 12.

We have commisioned our new ultra-low background VG 3600 mass spectrometer and made modifications to our furnace design to achieve extraordinarily low blanks ($<10^{-17}$ mol ^{40}Ar at 1000°C) without sacrificing temperature control. We are proceeding with a plan to acquire a CO_2 laser capability by attaching an IR transparent window (ZnSe) to a bakeable, ultra-high vacuum system. This viewport is currently under construction.

DISCLAIMER

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1. Background

A common ingredient in evaluation of virtually all energy sources is some form of temperature measurement. A complete description of exploitable geological sources, both geothermal and fossil fuel, requires an understanding of the temperature history of the system over extremely long times. Over the past ten years, we have been developing $^{40}Ar/^{39}Ar$ K-feldspar thermochronometry (*e.g.*, Harrison and McDougall, 1982; Harrison and Be, 1983; Lovera *et al.*, 1989; Harrison *et al.*, 1991). This approach provides information of a samples integrated temperature-time history in the range 130 to 350°C, along with a systematic basis to separate these two parameters. The advantage of this method over other currently used thermometers (*e.g.*, vitrinite reflectance) is more than just the simplicity of the thermally activated reaction; the absolute time framework which accompanies the thermometry allows assessment of the geological age of thermal excursions. Apatite fission track dating (*e.g.*, Gleadow *et al.*, 1983) is a complimentary approach that provides extention of temperature coverage into the 80 to 120°C range, but the millionfold lower decay constant for ^{238}U relative to ^{40}K restricts the resolution of the resulting thermal history (*e.g.*, Corrigan, 1991).

By irradiating K-feldspars with a known dose of fast neutrons, a portion of the ^{39}K transmutes to ^{39}Ar, an isotopically distinct but chemically identical form of ^{40}Ar, a daughter product of naturally radioactive ^{40}K. Thus, the $^{40}Ar/^{39}Ar$ ratio of a geological sample is proportional to its age. If the sample has been heated in the temperature range 130 to 350°C for geological periods, the transport kinetics of ^{40}Ar in K-feldspar are sufficiently rapid to cause partial outgassing of the sample. The rate of gas loss is exponentially dependent on temperature but proportional to the square root of the heating duration. Thus, if the diffusion parameters for Ar transport in K-feldspar are known or can be obtained via the extraction experiment, a partially outgassed sample can yield information related to the ages of both the source rock and reheating event, as well as the temperature of that later event.

Many and perhaps most $^{40}Ar/^{39}Ar$ age spectra for slowly cooled alkali feldspars are significantly different from model age spectra calculated assuming a single diffusion-domain size. In addition, Arrhenius plots calculated from the measured loss of ^{39}Ar during the step heating experiment show departures from linearity that are inconsistent with diffusion from domains of equal size. Lovera *et al.* (1989) extended the single diffusion-domain closure model of Dodson (1973) to apply to minerals with a discrete distribution of domain sizes. The discrete diffusion-domain distribution model offers an internally consistent explanation for the commonly observed features of alkali feldspar age spectra and their associated Arrhenius plots. Because these domains contain a range of closure temperatures, Lovera *et al.* (1989) found that a single K-feldspar sample may reveal a broad segment of a cooling history, rather than the single datum usually expected. The excellent agreement among cooling history segments for coexisting samples with differing activation energies gives confidence that extrapolations of the kinetic results down-temperature are meaningful as non-linear behavior in any one sample would displace that segment off the shared cooling history (Harrison, 1990).

Recently, we have tested and confirmed the general predictions of the domain distribution theory by performing non-conventional $^{40}Ar/^{39}Ar$ extraction experiments involving isothermal heating, short and long duration heating (50 sec to 3 days) and cycled heating/cooling experiments Lovera *et al.*, 1991). These studies showed that the diffusion domain distribution parameters (domain size, ρ, and volume fraction, ϕ) can be adequately obtained through fits to both the age spectrum (formed over millions of years) and the Arrhenius results (obtained in the laboratory over a matter of hours) assuming that the activation energies of all domain sizes are equal, or nearly so. Our recent analyses of small (~400 μm) individual crystals indicate that the domains are an intrinsic property of potassium feldspars that are not separable at the micron scale (Lovera *et al.*, 1991). Because the form of Arrhenius plots varies with laboratory heating schedule for samples with a domain size distribution, we proposed an alternative plot (Richter *et al.*, 1991; Lovera *et al.*, 1991) in which the log of the deviation from the diffusion law for the earliest released argon (r_0) is plotted against cumulative $\%^{39}Ar$ released. The $\log(r/r_0)$ plot yields domain size data independent of laboratory heating schedule, provided all domains share the same activation energy.

In our first year of funding under the auspices of grant DE-FG03-89ER14049, we have investigated four interrelated aspects of K-feldspar thermochronology; 1) definition of K-feldspar domains, 2) refinements to the multi-domain model, 3) the thermal evolution of the Valles Caldera, and 4) the continued development of microanalysis.

2. K-feldspar Thermochronology 1990-1991

2.1 Definition of K-feldspar Domains

The most surprising aspect to arise out of our recent work (Lovera *et al.*, 1989,1991; Harrison, 1990; Richter *et al.*,1991; Ryerson and Harrison, 1990; Harrison *et al.*, 1991) is the suggestion that virtually all low temperature potassium feldspars contain sub-grain diffusion domains and that their distribution is discrete rather than continuous. Clearly, a deeper appreciation of this phenomenon would follow from the determination of the features that control the loss of argon from feldspars. When examined by optical, X-ray and transmission electron microscopy (TEM) methods, an assortment of features in low temperature feldspars are observed, such as grain boundaries, albite and pericline twins, tweed structure, dislocation subgrains and tangles, stepped twins, orthoclase enclaves in microcline, exsolution lamellae of varying widths, anti-phase boundaries, coherent and noncoherent perthite boundaries, micro-pores, healed cracks, and cleavage, that could be possible candidates for argon permeable boundaries (Eggelton and Buseck, 1980; MacLaren, 1978; Fitz Gerald and MacLaren, 1982; Zeitler and Fitz Gerald, 1986; Smith and McLaren, 1983; Yund, 1983a,b,c; Yund *et al.*, 1981; Harrison and McDougall, 1981; Parsons *et al.*, 1988).

No one of these above mentioned features recommends itself to us above others as capable of regulating the widespread occurrence of a discrete distribution of diffusion domain sizes. Further complicating this assessment are possible changes to the microstructure that occur during heating (*e.g.*, Smith *et al.*, 1987). The extent to which we mistakenly ascribe domain size qualities to activation effects will influence our estimates of the absolute and relative dimensions of the responsible boundaries. To identify which, if any, of the above features control argon diffusion first requires a clear understanding of the relative contributions of frequency factor and physical size to the observed variations.

2.1.1 TEM and Light Microscopy

In September 1990, Harrison travelled to the Australian National University to begin a TEM and light microscope study of K-feldspar sample MH-10 in collaboration with Dr. John Fitz Gerald. We have examined not only 'virgin' K-feldspar separated from crushed samples of MH-10, but also samples heated in vacuum for 70 min at temperatures of 750, 950, and 1100^{O}C. This range of material was examined to characterize both the initial microstructure and any changes due to heating in the Ar-diffusion studies. Following optical-scale examination of ultra-thin sections (~10 μm thickness), coarse grains of the samples were prepared using conventional Ar-ion beam thinning techniques (*e.g.*, Tighe, 1976) for imaging and diffraction investigations using a JSEM 200B TEM operated at 200 kV. Although it is difficult to obtain a three dimensional view from two dimensional images, our preliminary results suggest a plausible correspondence between the imaged features and the diffusion results.

The MH-10 rock shows almost no evidence of plastic deformation, and the K-feldspar does not possess networks of dislocations which might define a subgrain structure. Three classes of substructure are present in the K-feldspar, but only the third appears to have been affected at all by laboratory heating:

(1) Cross hatched extinction (light microscope, maximum extinction angles of $\pm$ 18^{O} indicate maximum microcline) is common but variably developed. TEM reveals almost no albite/pericline twinning, only tweed microstructure.

(2) Turbid zones exist within this K-feldspar, but only 5-10 volume % of the mineral is affected. Micropores, <1 to 2 μm, characterize these regions, which often also feature blebs of albite, 2 to 40 μm diameter. TEM shows these 'modified' zones to be very complex with intricate twin and tweed structures at the

sub-micron scale and numerous dislocation and strain features. Adjacent micropores do not appear to be connected, although light microscopy indicates many of the structures have originated at fractures.

(3) Exsolution lamellae. Albite lamellae (>1 x 20 μm, separated by 1 μm, light microscopy) are rare (~2%). TEM shows submicroscopic lamellae are more common, occurring in about 20% of K-feldspar. These lamellae, 0.01 x 0.2-1 μm, separated by 0.1 to 0.5 μm, are disk-shaped and probably have a semi-coherent relationship to the host K-feldspar. Submicroscopic lamellae appear to have been removed by heating to 950 and 1100^{o}C.

The largest domain size identified by experiment (see section 2.1.2) is approximately 50 μm. This order of magnitude corresponds to the size of blocks of K-feldspar defined by the network of fractured/turbid zones in MH-10. The smallest domain size inferred from diffusion analysis is ~0.1 μm which corresponds to the separation observed between albite exsolution lamellae. In addition, the volume of material containing the finest scale of perthite is similar to the estimated volume fraction of the smallest domain size in MH-10. Despite this promising agreement, several anomalies remain.

(1) No clear candidate has been identified for a domain of intermediate size.

(2) The diffusion analysis suggests that the domains of different sizes be independent. The observed structures may be nested.

(3) The analysis also requires that domain boundaries be effectively open pathways to grain exteriors. The degree of coherence between albite and K-feldspar lattices might involve only limited enhancement of diffusivity at each lamellar interface, also the relationship between adjacent disks of lamellae suggests that connectivity may be less than ideal.

2.1.2 Thermal Stability of Domains

Our current view is that the only experimental criterion critical to extraction of meaningful diffusion and domain size information is not exceeding the incongruent melting temperature of K-feldspar (~1150^{o}C). However, Zeitler (1987) observed an apparent difference between the Arrhenius plot of a K-feldspar sample that had been heated prior to irradiation compared to the unheated sample. Although we had not ourselves observed this effect, we proposed a key and simple experiment to test our domain hypothesis and the implicit assumption that the natural domain structure is undisturbed by laboratory heating. Although homogenization and disordering changes are unlikely to occur during the laboratory experiment (*e.g.*, Hokanson and Yund, 1986; Yund, 1983c), reversible displacive changes do occur (*e.g.*, Smith *et al.*, 1987) which might affect the domain structure. By interrupting the age spectrum experiment after the smallest domain has degassed (by heating to 950^{o}C) and re-irradiating it, we were able to evaluate whether the smallest domain size has been altered or remains unaffected by heating. Our first such experiment revealed a clear decrease in the diffusion coefficient by an order of magnitude suggesting that the smallest domain had been erased during heating. However, a second experiment to confirm this finding revealed no such change in the diffusion character of MH-10. We have redesigned the experiment and are currently performing additional experiments to assess if the domainal structure remains robust throughout the experiment or if these features are annealed once degassed.

2.1.3 Crushing and Diffusion Experiments

Although the precise nature of the diffusion domains is as yet unclear, what we do know from our analysis of K-feldspar age spectra and associated Arrhenius plots is the relative size of the domains. For example, the age spectrum and $\log(r/r_o)$ plot for sample MH-10 reveal the presence of three diffusion domains, the largest being three times the size of the intermediate domain and fifty times larger than the smallest. The most extreme contrast so far observed is a factor of a hundred, although differences in assumed diffusion geometry can change this to some degree.

Having observed the same range of domain sizes within 400 μm diameter single crystals of MH-10 as that found in aggregates, we can reasonably infer that the largest domain is no bigger than hundred's of microns and the smallest is less than about 10 μm. We have recovered finer grained samples of MH-10 that we have irradiated and analyzed. A fraction of MH-10 with a diameter of about 40 μm (MH-10.g) yields the $\log(r/r_o)$

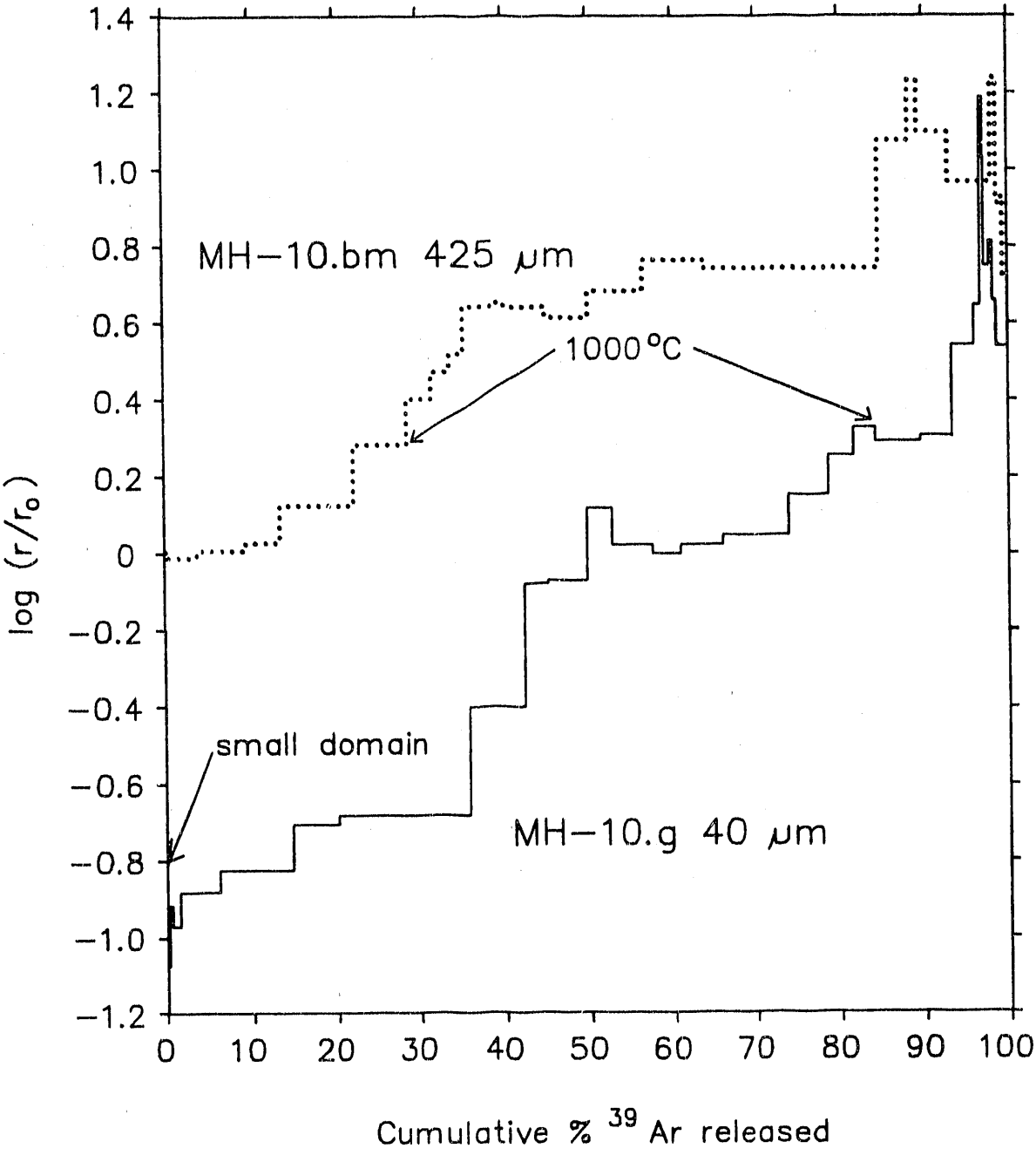

Figure 1 - log (r/r_o) plot of coarse grained MH-10 (MH-10.bm) and very fine grained MH-10 (MH-10.g). The 40 micron sized material has lost most of its large domain (maximum value is approximately 0.6 compared to 1.1 in the 425 micron aggregate) and increased the volume fraction of the small domain. Note also the contrasting gas losses at 1000°C.

plot shown in Fig. 1 together with the $\log(r/r_o)$ plot for the corase grained material (MH-10.bm). Although the largest domain size has clearly been annihilated, there are still three diffusion domain sizes present in the sample. It may appear that the crushing of the sample has introduced an even smaller domain (*i.e.*, the data plotting at -0.8), but note that this is precisely the position (indicated by the arrow) of the smallest domain size predicted from the orignal experiment on the coarse grained sample. Clearly we have dramatically increased the volume fraction of the smallest domain, but have we done this by concentrating the small domain in the finest seive fractions or by creating more of the small domain by size reduction of the large domain? Although there is likely a contribution from each, the decrease in the K-Ar age of the 40 μm experiment of 10 Ma compared with the 400 μm sample suggests the former explanation may be the dominant effect. By isolating the largest domain size to be between 40 and 100 μm, this implies that the smallest domain is order 1 μm in size. An addition effect, diffusion compensation, discussed in the next section further reduces this estimate to order 0.1 μm.

2.2 Refinement of the Multiple Domain Hypothesis

2.2.1 Multiple Activation Energies

Although our extension of the single diffusion domain/activation energy closure model to a discrete distribution of domain sizes appears to reconcile $^{40}Ar/^{39}Ar$ age spectra with their associated Arrhenius plots, we began last year to focus on small remaining discrepancies, particularly apparent in $\log(r/r_o)$ plots, that suggested that some, and perhaps most, alkali feldspars contain diffusion domains with activation energies that may vary by as much as 8 kcal/mol. An extraordinary consequence of even relatively small variations in activation energy between domains is that the shape of an age spectrum can change dramatically by varying the laboratory heating schedule. We find that Arrhenius and $\log(r/r_o)$ plots have the potential to reveal even small differences in activation energy (~2 kcal/mol) between domains, at least in cases where the domains are well separated in size. Variations in activation energy of ~5 kcal/mol can result in differences in calculated closure temperature of up to 30°C from that obtained assuming equal activation energies for all domains. Overestimates of apparent activation energy and other inconsistencies resulting from reversed heating experiments are thought to reflect annealing of subgrain features which define the smallest diffusion domain size. Although introduction of multiple activation energies leads to one too many degrees of freedom for complete assessment of the distribution parameters, use of the diffusion compensation relationship provides a way to assess the relative distribution of diffusion domain sizes. These results were written up during 1990 and are in press in Geochimica et Cosmochimica Acta (Harrison *et al.*, 1991).

2.3 Valles Caldera VC-2B

As part of a long-term investigation of the geothermal potential of the Valles Caldera, north-central New Mexico, the U.S. Department of Energy recently completed VC-2B, currently the deepest, hottest, continuously cored hole in North America, reaching a depth of 1.762 km (Gardner *et al.*, 1989). The first 1.558 km of rock penetrated consists of altered Phanerozoic sediments, with the hole bottoming in Proterozoic quartz monzonite at a depth and temperature of 1.762 km and 295°C, respectively. The special character of these rocks and our previous analyses of basement feldspars recovered from Valles cores suggests that the use of K-feldspar thermochronology may reveal important details of the temperature-time evolution of this hydrothermal system. This information is important not only for assessing the geothermal potential, but may enhance other investigations of the geochemistry and petrology of the recovered cores and/or fluids from the Sulphur Springs wells (VC-2A and VC-2B).

We have previously studied samples from the Fenton Hill Hot-Dry-Rock wells on the western flank of the Valles Caldera (Harrison *et al.*, 1986). Using K-feldspar thermochronology, we found that the duration of heating in this well was less than 10^5 years and thus apparently not linked to the magma system which erupted the Upper Bandelier Tuff 1.13 Ma ago (Spell *et al.*, 1990) leading to caldera collapse. In contrast, an analysis of a Precambrian K-feldspar from the bottom of a deep well (3.24 km) from within the caldera (Baca-12),

currently at a temperature of 340°C, yielded a highly outgassed $^{40}Ar/^{39}Ar$ age spectrum suggestive of a heating duration of order 10^6 years (reported in Harrison *et al.*, 1986). We have followed up these results using samples from the bottom of VC-2B and the approach described above.

We have analysed K-feldspar single crystals from depths of 1.558 (1.10 mg) and 1.762 (1.06 mg) km depth by the $^{40}Ar/^{39}Ar$ method with a view to elucidating the effects of reheating from intrusion of the Bandelier magma chamber and/or subsequent intrusions related to postcollapse rhyolites. The resulting age spectra are similar and suggest no significant difference in the thermal histories experienced by the two samples. Both reveal minor excess argon in the first 5% of ^{39}Ar released which is superimposed on spectra which rise from apparent ages of 200 to 300 Ma to as old as 0.9 to 1.0 Ga in the high temperature steps. These spectral forms are similar to our previous $^{40}Ar/^{39}Ar$ analyses of basement feldspars from this region (Harrison *et al.*, 1986; Harrison and Burke, 1988). Excess argon in the initial steps masks documentation of minor argon loss from these samples difficult but it is clear that less than 5% argon loss has been experienced. Using this value as an upper limit to argon loss together with the Arrhenius parameters (E = 62 kcal/mol; $D_o/r_o^2 = 5 \times 10^9$ /sec) and present temperature (295°C) of the deepest sample yields an estimate of heating duration at or near peak temperature of < 10,000 years. This result is more similar to the estimate from the Hot-Dry-Rock drill hole than Baca-12 and suggests that the Sulphur Springs hydrothermal system may be unrelated to the caldera forming magmatic event.

2.4 Developments in Microanalysis

The ability to analyze small (~400 μm) single crystals with precise and accurate temperature control has already paid dividends in our understanding of K-feldspar domains. Clearly, the ability to analyze still smaller crystals will allow us to make finer distinctions in thermal history analysis. Our existing VG 1200S rare gas mass spectrometer was this year supplemented by a VG 3600 mass spectrometer. The new mass spectrometer is specified to have higher mass resolution (MRP = 600) and an order of magnitude lower background levels (*e.g.*, 10^{-18} mol at mass 36) than the 1200S. We have just this month achieved the background specification and will initiate use of this spectrometer by performing laserprobe measurements on MH-42 K-feldspar to assess the significance of this approach in assessing diffusion lengthscales in K-feldspar. To exploit this lower background, we have begun experimenting with new furnace designs to achieve lower blanks yet (say, $< 10^{-17}$ mol ^{40}Ar) without sacrificing temperature control.

In general, K-feldspar samples are heated in a Ta crucible within a double-vacuum furnace (Staudacher *et al.*, 1978; Harrison and Fitz Gerald, 1986). Our recent modification is to immerse in water the seals which separate the double-sided stainless-steel flange to which the Ta crucible is electron beam brazed, from the rest of the vacuum line. This arrangement has led to extremely low blanks (*e.g.*, 7×10^{-17} mol ^{40}Ar at 1000°C) being acheived (Harrison *et al.*, 1991). We are unsure whether this reflects cooling of surfaces that would otherwise leak due to differential thermal expansion, or whether the relatively viscous and low argon fluid is effectively sealing microcracks.

In cases where temperature control during heating is unimportant, laser heating of the feldspar sample imparts very low ^{40}Ar blanks and is a very convenient manner of heating. However, about one third of all alkali feldspars subjected to the beam of our 7 W Ar ion laser are completely transparent and fail to fuse. Even those that do fuse lose only about 60% of their radiogenic ^{40}Ar before melting and the subsequent loss of coupling with the light. An attractive alternative is to use a CO_2 laser which lases at 10.5 μm, a fundamental frequency of the Si-O bond, allowing fusion of any silicate at relatively low power. The drawback of this approach is that the CO_2 beam also couples with the materials conventionally used for viewports (*e.g.*, pyrex, quartz, sapphire) requiring alternative materials such as ZnSe or BaF_2. To our knowledge, no one has previously succeeded in attaching an IR transparent window to a bakeable, ultra-high vacuum system. After investigating the candidate materials, we chose to proceed with ZnSe as it is transparent to visible light, has a low vapor pressure, outgasses well in the extraction system, is bakeable to 200°C, and is resistant to thermal shock. We have contracted Line Light Lasers to develop a technique to sinter a Kovar glass-to-metal adapter to the ZnSe and mate this assembly to a conventional conflat flange. We anticipate testing later this year.

2.5 Other Accomplishments

- In this past year, we have re-commisioned our Nuclide 4.5-RSS-60 mass spectrometer (brought out from SUNY at Albany) for routine measurements of larger samples. The extraction line was completely rebuilt to be all-metal.

- Lovera, with assistance from Harrison, has refined, debugged and documented the Arrhenius and age spectrum program for publication (Lovera, 1991) and distribution to other interested geochronologists. Thus far, this software has been made available to the Australian National University, University of Houston, Exxon Production Research, Monash University, Caltech, Lehigh University, SUNY at Albany and University of Chicago.

3. Publications directly related to DOE funding of K-feldspar thermochronology appearing or in press from July 1, 1990 to March 1, 1991

1) Copeland P. and Harrison T.M. (1990) Episodic rapid uplift in the Himalaya revealed by $^{40}Ar/^{39}Ar$ analyses of detrital K-feldspars and muscovite. Geology 18, 354-357.

2) Copeland P., Harrison T.M. and Heizler M.T. (1990) $^{40}Ar/^{39}Ar$ single crystal dating of detrital muscovite and K-feldspar from ODP Leg 116, southern Bengal Fan: Implications for the uplift and erosion of the Himalaya. Proc. Oceanic Drilling Project, Sci. Results Vol. 116, 93-114.

3) Copeland P., Harrison T.M., and Le Fort P. (1990) Age and cooling history of the Manaslu granite: Implications for Himalayan tectonics. Jour. Volcanol. Geotherm. Res. 44 33-50.

4) Copeland P., Harrison T.M., Hodges K.V., Mareujol P., Le Fort P. and Pecher A. (1990) A Late Miocene-Early Pliocene thermal perturbation along the MCT related to movement on the MBT, central Nepal: Recurring tectonothermal consequences of collision. Jour. Geophys. Res. (in press).

5) Foster D.A., Harrison T.M., Copeland P. and Heizler M.T. (1990) Effects of excess argon within large diffusion domains of K-feldspar age spectra. Geochim. Cosmochim. Acta 54, 1699-1808.

6) Harrison T.M., Lovera O.M. and Heizler M.T. (1991) $^{40}Ar/^{39}Ar$ results for alkali feldspars containing diffusion domains with differing activation energy. Geochim. Cosmochim. Acta (in press).

7) Harrison T.M. (1990) Some observations on the interpretation of feldspar $^{40}Ar/^{39}Ar$ results. Isotope Geosci. 80, 219-229.

8) Heizler M.T. and Harrison T.M. (1991) The heating duration and provenance ages of rocks in the Salton Sea Geothermal Field, southern California. Jour. Vol. Geotherm. Res. 46.

9) Lovera O.M., Richter F.M. and Harrison T.M. (1991) $^{40}Ar/^{39}Ar$ geothermometry for slowly cooled samples having a distribution of diffusion domain sizes. Jour. Geophys. Res. 94, 17,917-17,935.

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11) Richter F.M., Lovera O.M., Harrison T.M. and Copeland P. (1991) Tibetan tectonics from $^{40}Ar/^{39}Ar$ analysis of a single potassium feldspar sample. Earth Planet. Sci. Lett. (in press)

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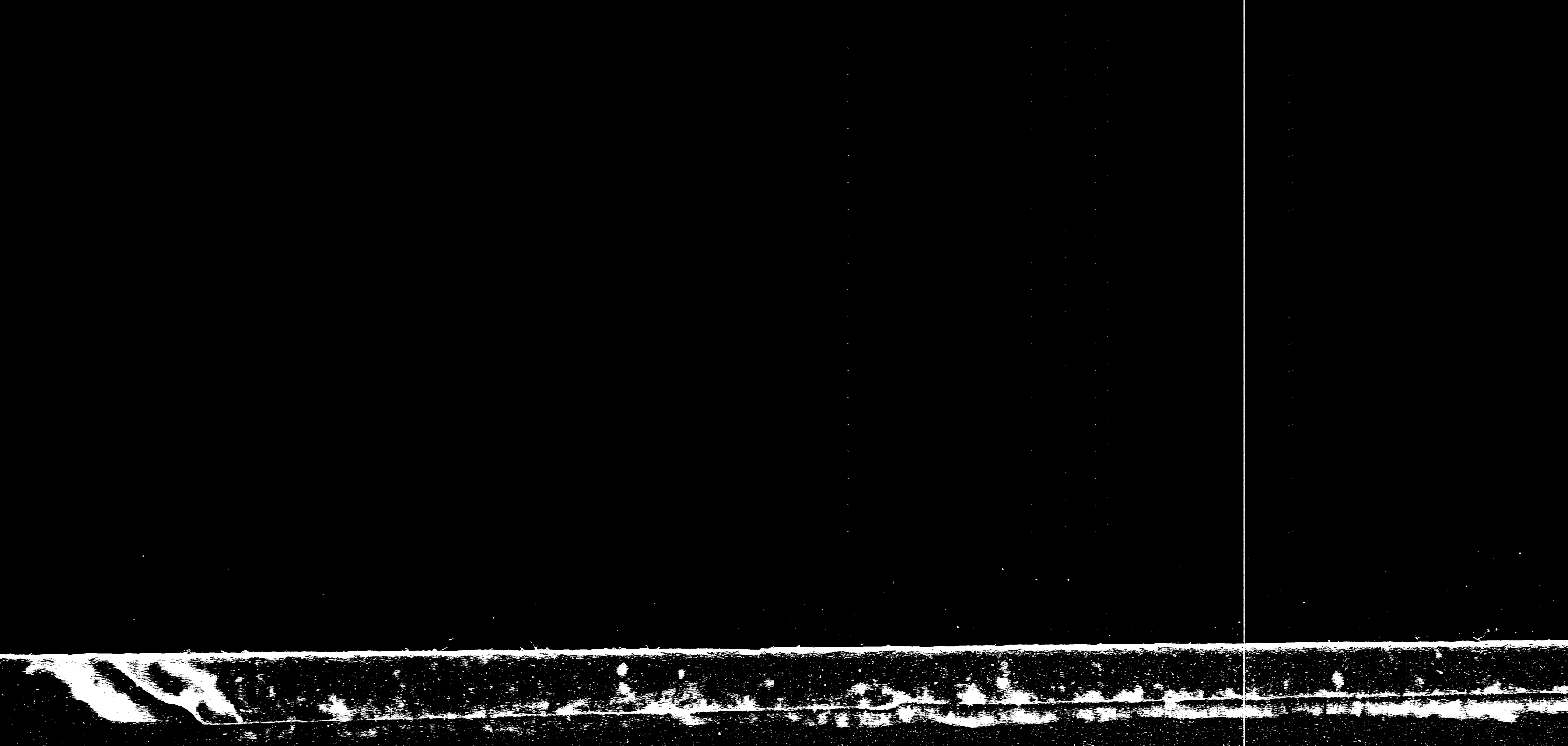

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