Thermochronology and Geobarometry of the Granite Mountains, southeast California; Exhumation of a Plutonic Complex During Collapse of the Sevier Orogen

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ABSTRACT

Mid-Tertiary tectonic overprinting in the eastern Mojave Desert region adds complication to describing and interpreting results of earlier Mesozoic tectonics. Thermochronologic data indicate the preservation of original Mesozoic isotopic signatures in the Granite Mountains, southeast California. These data include ages and cooling histories for Cretaceous plutons determined by U/Pb, $^{40}Ar/^{39}Ar$, and U-Th/He systematics. U/Pb zircon and $^{40}Ar/^{39}Ar$ hornblende ages are indistinguishable at 2σ errors suggesting Late Cretaceous intrusion and cooling through ~500 °C for Granite Mountain plutons. Thermal modeling of $^{40}Ar/^{39}Ar$ K-feldspar age spectra indicates continued rapid cooling down to ~150 °C. Cooling for plutons at such a high rate almost certainly requires tectonism. These data support increasing evidence for Late Cretaceous extension due to the gravitational collapse of the overthickened Sevier Orogen. U-Th/He apatite ages range from ~40 to ~20 Ma and correlate with elevation. These data may be interpreted as resulting from very slow cooling or an extended period of residence in the He partial retention zone, however, they may also be indicative of Mid-Tertiary Basin and Range tectonics playing a later role in the exhumation of this plutonic complex.

INTRODUCTION

In some areas of the North American Cordilleran interior evidence for rapid unroofing and cooling of mid-crustal rocks during the Late Cretaceous extensional collapse of the Sevier Orogeny is well documented (Foster et al., 1989; Wells et al., 1990; Hodges and Walker, 1992; Miller et al., 1995). However, in many areas this event is neither confirmed nor well dated, partly because mid-Cenozoic extension (Basin and Range tectonics) also took place in the region (Foster et al., 1990). This results in a lack of evidence for north-south continuity of Cretaceous extensional structures. This study focuses on the Granite Mountains, located in the eastern Mojave Desert of California, which are situated at the southernmost extent of the Sevier Orogenic belt, an area in which details of Late Cretaceous tectonics are incompletely understood (Fig. 1).

The main goals of this project are (1) to determine the depth and timing of emplacement for the major plutons that have been mapped in the Granite Mountains, (2) construct the subsequent cooling histories for these plutons, and (3) relate these results to known tectonic events that have affected the region. These goals will be met by answering the questions (1) What were the timing and rates of exhumation? and (2) What tectonic event(s) lead to the exhumation of the plutons of the Granite Mountains? Rapid Cretaceous exhumation as a result of extensional collapse of the Sevier orogeny is the hypothesis for this study.

Contraction and later extension of the Sevier Orogen were important events for the construction of the present day western North American landscape. With geochronological data being scarce and in many areas unavailable, the understanding of this major part of North America's tectonic history is limited. The results of this project will add to the knowledge of this widespread orogenic event at its southern most extent.

REGIONAL GEOLOGY

Sevier Orogeny

The Sevier thrust belt is a series of continuous contractional structures extending north-south through western North America (Armstrong, 1968) (Fig. 1). Deformation and plutonism of the Sevier Orogeny began in the Late Jurassic and by about Early Cretaceous time a continuous belt of east-vergent thrusting stretched from Canada to southeastern California (Burchfiel et al., 1992). To the west of this east-vergent foreland fold and thrust belt are associated Late Jurassic plutons and synmetamorphically-deformed rocks (Burchfiel et al., 1992). These Jurassic plutons (165 to150 Ma) cut earlier Mesozoic deformational fabrics, folds, and thrust faults (Burchfiel et al., 1992). The Sevier belt may be entirely younger than the plutons since the time of initial thrusting in the Sevier belt is unclear (Burchfiel et al., 1992).

Overthickening of continental crust resulting from contraction of the Sevier Orogen led to extensional collapse in the Late Cretaceous (Wells and Allmendinger, 1990; Wells, 1997). Extension in the Sevier hinterland has been well documented in Utah (Wells et al., 1990; Wells, 1997) and parts of California (Foster et al., 1989; Applegate et al., 1992; Miller et al., 1995). Mesozoic extensional structures and isotopic signatures related to the Sevier are discontinuous to the south due to younger overprinting of Cenozoic Basin and Range tectonics.

Granite Mountains

The Granite Mountains expose rocks ranging in age from Paleozoic to Cenozoic, but are dominated by Mesozoic igneous rocks (Howard et al., 1987) (Fig. 2). Aluminum-in-hornblende geobarometry indicates crystallization pressures of 6.0 to 7.5 kbar for Jurassic and Cretaceous granitoids in the northern Granite Mountains, corresponding to emplacement depths of 19 to 25 km (Young and Wooden, 1988).

In contrast with the heavily faulted Old Dad Mountains to the west, there are few faults in the interior of the range, but faults are present on the perimeter of the Granite Mountains (Howard et al., 1987) (Fig. 2). The Bull Canyon fault, a late Tertiary low-angle normal fault, dips outward from the range at 20-40^{o} north and northwest tracing around the northern base of the Granite Mountains (Howard et al., 1987) (Fig. 2). Separating the Granite Mountains from the Old Dad Mountains is the northwest-striking Bristol Mountains fault zone (Gamble, 1959a,b; Howard et al., 1987) (Fig. 2). Dipping northeast 70-80^{o}, the fault places Mesozoic plutonic rocks in the hanging wall over Tertiary supracrustal rocks in the footwall, indicating reverse motion (Howard et al., 1987).

The Granite Mountains belong to a region of the East Mojave Desert that records substantial extension and plutonism in the Jurassic, Cretaceous and Miocene (Howard et al., 1995). Late Cretaceous extension is recorded in the East Providence fault zone along the east side of the Providence Mountains as well as in the Piute and Old Woman Mountains to the southeast (Foster et al. 1990) and the New York Mountains north of the Providence Mountains (Beyene, 2000).

Providence Mountains

The Providence Mountains lie to the northeast of the Granite Mountains (Fig. 2). The southern region of these mountains consists of Mesozoic granitic plutons similar to those exposed in the Granite Mountains. Young and Wooden (1988) determined a mid-to shallow crustal emplacement depth of 8-16 km for these plutons using aluminum-in-hornblende geobarometry. Along the east side of this range is the East Providence fault zone (Fig. 2). This fault zone consists of several steep (~65°-75°) dipping down-to-the-west normal faults (Miller et al., 1995). The East Provident fault zone has been correlated as a segment of the East Mojave fault, which is an at least 70 km long north-to northwest-striking Late Cretaceous (~70 Ma) extensional structure spanning across the eastern Mojave Desert (Miller et al., 1995)

ANALYTICAL METHODS

A suite of samples was collected that covered the extent of the Granite Mountains and into the southern Providence Mountains. Four samples: Omar, Yoshi, Calvin, and Floyd, were selected from this suite based on the criteria that they (1) contain the correct mineral assemblages for isotopic dating techniques and geobarometry, (2) were representative of their host pluton, and (3) formed a transect across the Granite Mountains into the southern Providence Mountains. Omar was collected from the Providence, whereas Yoshi, Calvin, and Floyd are from the Granite Mountains (Fig. 2).

The isotopic dating techniques used in this research are U/Pb zircon geochronology (ion microprobe), $^{40}Ar/^{39}Ar$ thermochronology on hornblende and K-feldspar, and U-Th/He thermochronology on apatite. The aluminum-in-hornblende geobarometer will be used to determine depth of crystallization for the plutons.

At this point in the research the geobarometry is currently incomplete. U/Pb zircon, $^{40}Ar/^{39}Ar$ hornblende and K-feldspar, and U-Th/He apatite dating has been completed and a preliminary interpretation of these data is presented in this paper.

RESULTS

U/Pb Geochronology

Zircons were analyzed at the National Ion Probe facility at UCLA. U/Pb zircon ages are interpreted as the age of crystallization for the pluton because zircons have a closure temperature for the retention of Pb exceeding 900 °C (Cherniak and Watson, 2000), whereas ~750 °C is the crystallization temperature for granitic bodies. The zircon standard used for these analyses was AS-3 which yields a U/Pb age of 1099.1 ± 0.5 Ma (Paces and Miller, 1993). Because the samples involved are Mesozoic in age, the data are presented using Tera-Wasserburg concordia U/Pb diagrams (Tera and Wasserburg, 1972).

Calvin

Eight zircon crystals from a Granite Mountain pluton described by Miller et al. (1985) as a porphyritic monzogranite (termed the Granite of Arroweed where it outcrops in the southern Providence Mountains), gave concordant ages yielding a weighted mean age of 75 ± 1 Ma (Fig. 3). Two older inherited cores were found with ages of ~121 and ~ 92 Ma. The eight ages used for the weighted mean age were indistinguishable at 2σ errors, yielding an MSWD of zero and 100% probability of fit.

Floyd

Out of nine zircons analyzed from a granodiorite in the center of the range, one inherited core was found with an age of ~119 Ma. The remaining eight analyses yielded a weighted mean age of 73 ± 1 Ma with an MSWD of 0.09 and a 77% probability of concordance (Fig. 4).

Yoshi

A spotted quartz monzonite mapped as Jurassic by Miller et al. (1985) was determined to be a Cretaceous pluton. Twelve zircon analyses from this pluton, which is located in a complex region containing multiple plutons, showed the presence of three inherited Jurassic cores (~151 Ma, ~156 Ma, and ~167 Ma) and one younger zircon yielding an unusually young age of 58 ± 3 Ma which can most likely be explained best by Pb loss. The remaining eight analyses gave a weighted mean age of 77 ± 1 Ma. These data showed a 95% probability of concordance and an MSWD of 0.003 (Fig. 5).

Omar

A pluton described as the quartz monzonite of Goldstone, ranging from quartz monzonite to quartz syenite and quartz monzodiorite (Miller et al., 1985), gave a weighted mean age from seven analyses of 164 ± 3 Ma (Fig. 6). These data have an MSWD of 0.088 and a 77% probability of concordance. This age is consistent with U/Pb zircon and K/Ar biotite ages determined by Miller et al. (1985).

$^{40}Ar/^{39}Ar$ Thermochronology

Hornblende and K-feldspar were analyzed by the $^{40}Ar/^{39}Ar$ method. The closure temperature for argon in hornblende is ~500 °C (McDougall and Harrison, 1999; Harrison, 1981). K-feldspar age spectra can be modeled to define a continuous cooling history from ~350 to ~150 °C (McDougall and Harrison, 1999; Lovera, 1992).

Discussion of $^{40}Ar/^{39}Ar$ Ages

The hornblende ages determined for Calvin, Floyd, and Yoshi are all indistinguishable from the crystallization zircon ages previously discussed. These samples yielded nearly ideal flat age spectra. Calvin (Fig. 7) and Floyd (Fig. 8) gave plateau ages of 74.8 ± 0.4 and 76.5 ± 0.5 Ma respectively. Yoshi (Fig. 9) gave a total gas age of 78.7 ± 0.4 Ma. Although there was no plateau, the relatively flat age spectra, high radiogenic ^{40}Ar yields, and the agreement with the U/Pb age gives confidence in the age calculated. Although there is a slight difference between the U/Pb and $^{40}Ar/^{39}Ar$ ages, they overlap within 2σ errors and are therefore considered to be indistinguishable. Omar (Fig. 10) yielded a total gas age of 286.2 ± 1.4 Ma. The discordant age spectra and younger U/Pb age suggest this is an erroneously old age due to possible alteration in the sample and excess argon.

$^{40}Ar/^{39}Ar$ age spectra for K-feldspars were modeled to define continuous cooling curves for the plutons from ~350 to ~150° C using computer programs created by Oscar Lovera (Lovera, 1992). Calvin, Floyd, and Yoshi were modeled and yielded cooling curves from ~340 to ~150°C, ~300 to ~150°C, and ~275 to ~125°C respectively. These data suggest rapid cooling at ~73 to ~68 Ma supporting the hypothesis of Late Cretaceous exhumation during Sevier related extensional tectonics (Foster et al., 1989; Wells et al., 1990; Applegate et al., 1992; Hodges and Walker, 1992; Beyene, 2000)

U-Th/He Thermochronology

Apatite separates were run for U-Th/He thermochronology at the California Institute of Technology. These data represent the timing of cooling for the plutons through ~70° C. The ages determined are Calvin: 23.6 ± 0.8 Ma, Floyd: 40.2 ± 3.3 Ma, Yoshi: 21.2 ± 2.2 Ma, and Omar: 35.1 ± 2.3 Ma (all errors at 1σ). These data have a correlation between age and elevation, which may be explained by either very slow cooling following the Late Cretaceous tectonics or a prolonged residence in the He partial retention zone.

CONCLUSIONS

U/Pb zircon and $^{40}Ar/^{39}Ar$ hornblende and K-feldspar data indicate Late Cretaceous intrusion and rapid cooling through ~100° C for plutons from the Granite Mountains. Cooling of plutons at such a high rate is indicative of tectonic events or very shallow intrusion which preliminary data from Young and Wooden (1988) argues against. The U-Th/He apatite ages suggest that the final movement upwards to the surface for the plutons took place from Late Eocene to Early Miocene (i.e. Basin and Range tectonism). Completion of the geobarometry is expected to complete the story and support these interpretations.

ACKNOWLEDGEMENTS

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REFERENCES CITED

Allmendinger, R. W., 1992, Fold and thrust tectonics of the western United States Cordillera, exclusive of the accreted terranes, *in* Burchfiel, B. C., Lipman, P., and Zoback, M. L., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-3, p. 583-607.

Applegate, J.D.R., Walker, J.D, and Hodges, K.V., 1992, Late Cretaceous extensional unroofing in the Funeral Mountains metamorphic core complex, California: Geology, v. 20, p. 519-522.

Armstrong, R.L., 1968, Sevier orogenic belt in Nevada and Utah: Geological Society of America Bulletin, v. 79, p. 429-458.

Beyene, M.A., 2000, Kinematics and Timing of the Pinto Shear Zone, New York Mountains, northeastern Mojave Desert, California [M.S. Thesis]: Las Vegas, Nevada, University of Nevada, Las Vegas, 155 p.

Burchfiel, B.C., Cowan, D.S., and Davis, G.A., 1992, Tectonic overview of the Cordilleran orogen in the western United States, *in* Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., eds., The Cordilleran Orogen: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. G-3, p. 407-479.

Cherniak, D.J. and Watson, E.B., 2000, Pb diffusion in zircon: Chemical Geology, v. 172, p. 5-24.

Foster, D.A., Harrison, T.M., and Miller, C.F., 1989, Age, inheritance, and uplift history of the Old Woman-Piute Batholith, California and implications for K-feldspar age spectra: Journal of Geology, v. 97, p. 232-243.

Foster, D.A., Harrison, T.M., Miller, C.F., and Howard, K.A., 1990, The $^{40}Ar/^{39}Ar$ thermochronology of the eastern Mojave Desert, California, and adjacent western Arizona with implications for the evolution of metamorphic core complexes: Journal of Geophysical Research, v.95, p. 20,005-20,024.

Fox, L. K., and Miller, D. M., 1990, Jurassic granitoids and related rocks of the southern Bristol Mountains, southern Providence Mountains, and Colton Hills, Mojave Desert, California. *in* Anderson, J.L. (ed) The nature and origin of cordilleran magmatism. Geological Society of America Memoir 174: p. 111-132.

Gamble, J., 1959a, Geology and mineral resources of Township 8 North, Ranges 11 and 12 East, San Bernardino Base and Meridian, San Bernardino County, California: San Francisco, California, Southern Pacific company, unpublished report and 1:24,000-scale map, 22 p.

Gamble, J., 1959b, Geology and mineral resources of Township 9 North, Ranges 11 and 12 East, San Bernardino Base and Meridian, San Bernardino County, California: San Francisco, California, Southern Pacific Company, unpublished report and 1:24,000-scale map, 18 p.

Harrison, T.M., 1981, Diffusion of ^{40}Ar in Hornblende: Contributions to Mineralogy and Petrology, v. 78, p. 324-331.

Hodges, K.V., and Walker, J.D., 1992, Extension in the Cretaceous Sevier orogen, North American Cordillera: Geological Society of America bulletin, v. 104, p. 560-569.

Howard, K.A., Kilburn, J.E., Simpson, R.W., Fitzgibbon, Todd T., Detra, D.E., Raines, G.L, and Sabine, C., 1987, Mineral resources of the Bristol/Granite Mountains Wilderness Study Area, San Bernardino County, California: U. S. Geological Survey Bulletin, Report: B 1712-C, p.C1-C18.

Howard, K.A., McCaffrey, K.J.W., Wooden, J.L., Foster, D.A., and Shaw, S.E., 1995, Jurassic thrusting of Precambrian basement over Paleozoic cover in the Clipper Mountains, southeastern California, *in* Miller, D.M., and Busby, C., Jurassic Magmatism and Tectonics of the North American Cordillera: Boulder, Colorado, Geological society of America Special Paper 299, p. 375-392.

Howard, K.A., 2000, personal communication

Lovera, O.M., 1992, Computer Programs to Model $^{40}Ar/^{39}Ar$ Diffusion Data from Multidomain Samples: Computers and Geosciences, v. 18, p. 789-813.

McDougall, I. And Harrison, T.M., 1999, Geochronology and Thermochronology by the $^{40}Ar/^{39}Ar$ Method, Oxford University Press, New York, NY, 269 p.

Miller, D.M., Glick, L.L., Goldfarb, R., Simpson, R.W., Hoover, D.B., Detra, D.E., Dohrenwend, J.C., and Munts, S.R., 1985, Mineral resources and mineral resource potential of the South Providence Mountains Wilderness Study Area, San Bernardino County, California: U.S. Geological survey Miscellaneous Field Studies Map MF-1780-A, 29 p., scale 1:62,500.

Miller, D.M., Wells, M.L., Dewitt, E., Walker, J.D., and Nakata, J.K., 1995, Late Cretaceous extensional fault system across the northeastern Mojave Desert: San Bernardino County Museum Association Quarterly, v. 43, p. 77-84.

Paces, J.B. and Miller, J.D., 1993, Precise U-Pb Ages of Duluth Complex and Related Mafic Intrusions, Northeastern Minnesota: Geochronoligcal Insights to Physical, Petrogenetic, Paleomagnetic, and Tectonomagmatic Processes Associated with the 1.1 Ga Midcontinent Rift System: Journal of Geophysical Research, v. 98, p. 13,997-14,013.

Tera, F. and Wasserburg, G.J., 1972, U-Th-Pb Systematics in Three Apollo 14 Basalts and the Problem of Initial Pb in Lunar Rocks: Earth and Planetary Science Letters, v. 14, p. 281-304.

Wells, M.L., Dallmeyer, R.D., and Allmendinger, R.W., 1990, Late Cretaceous extension in the hinterland of the Sevier thrust belt, northwestern Utah and southern Idaho: Geology, v. 18, p. 929-933.

Wells, M.L., 1997, Alternating contraction and extension in the hinterlands of orogenic belts: An example from the Raft River Mountains, Utah: Geological Society of America Bulleting, v. 109, p. 107-126.

Young, E.D. and Wooden, J.L., 1988, Mid-crustal emplacement of Mesozoic granitoids, eastern Mojave Desert; Evidence from crystallization barometry: Geological Society of America Abstracts with Programs, v. 20, p. 244.

Young, E.D., Wooden, J.L., Shieh, Y-N, and Farber, D., 1992, Geochemical evolution of Jurassic diorites from the Bristol Lake region, California, USA and the role of assimilation: Contributions to Mineralogy and Petrology, v. 110, p. 68-86.

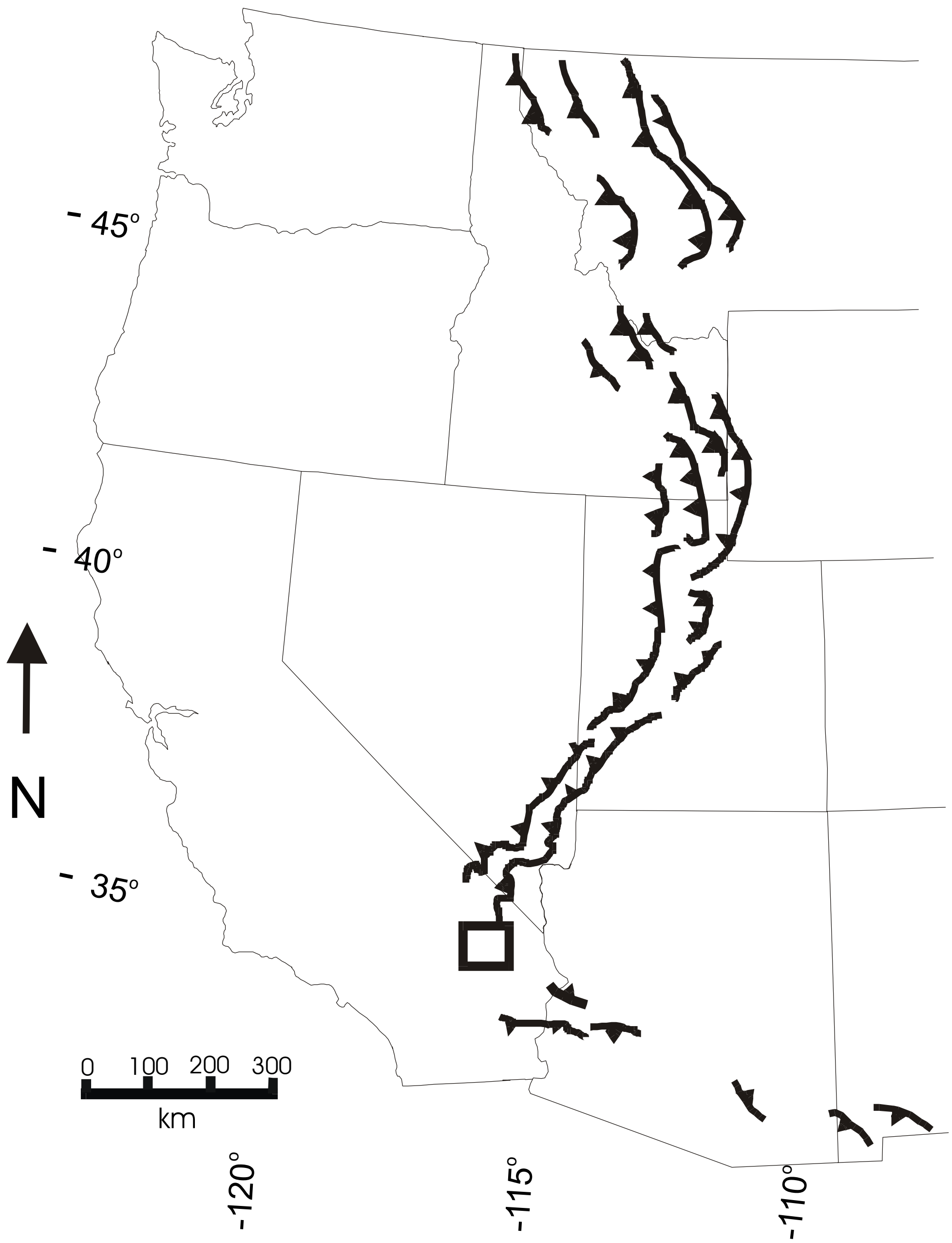


Figure 1. Map of major thrust faults of the Sevier orogenic belt extending from Canada to southeastern California. Modified from Lageson and Schmitt (1994); (compiled from Allmendinger, 1992; Poole et al., 1992; and Rodgers and Janecke, 1992). Square represents study area in the Mojave Desert at the southern extent of the Sevier belt.

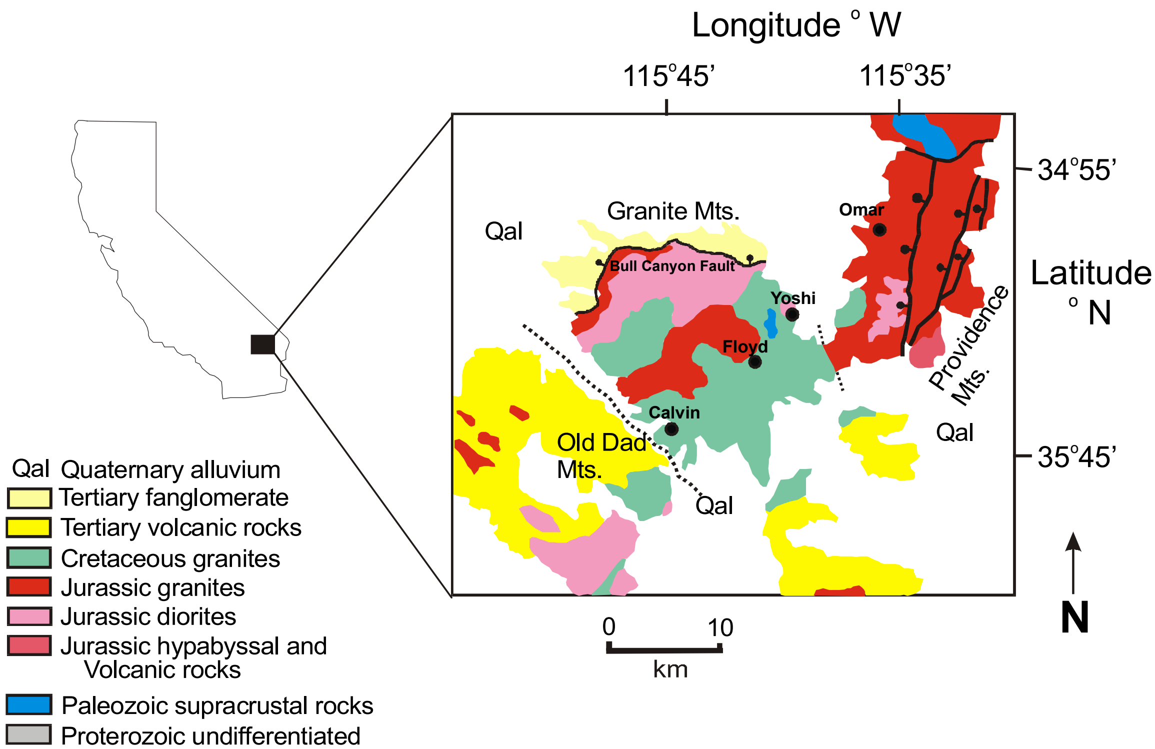
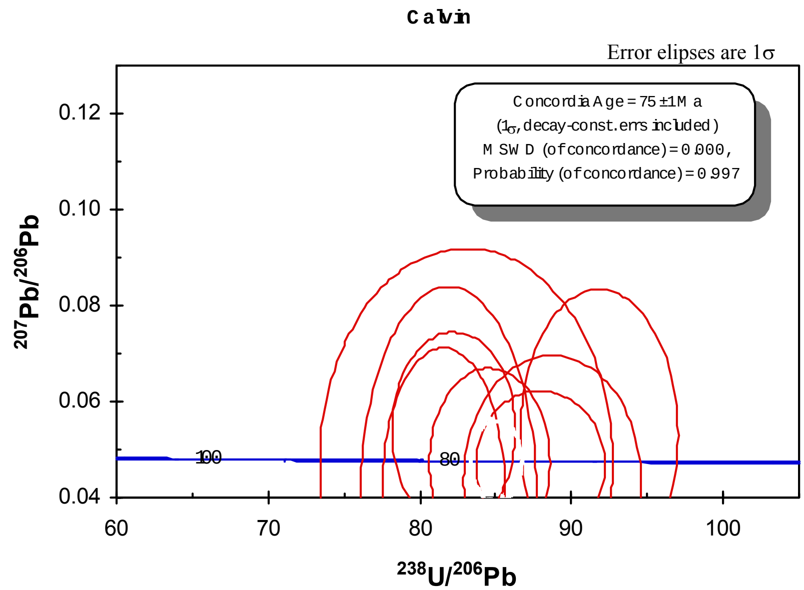


Figure 2. Geologic map of Granite Mountains and Providence Mountains in the eastern Mojave Desert. After Young et al. (1992) and Miller et al. (1995). Map shows different plutons mapped in the Granite Mountains as well as the Jurassic and Cretaceous units that are also exposed in the southern Providence Mountains, along with locations of samples used in this study. Fault lines in the Providence Mountains depict the East Providence fault zone. Dashed line between Old Dad Mts. and Granite Mts. represents the Bristol Mountains fault zone.



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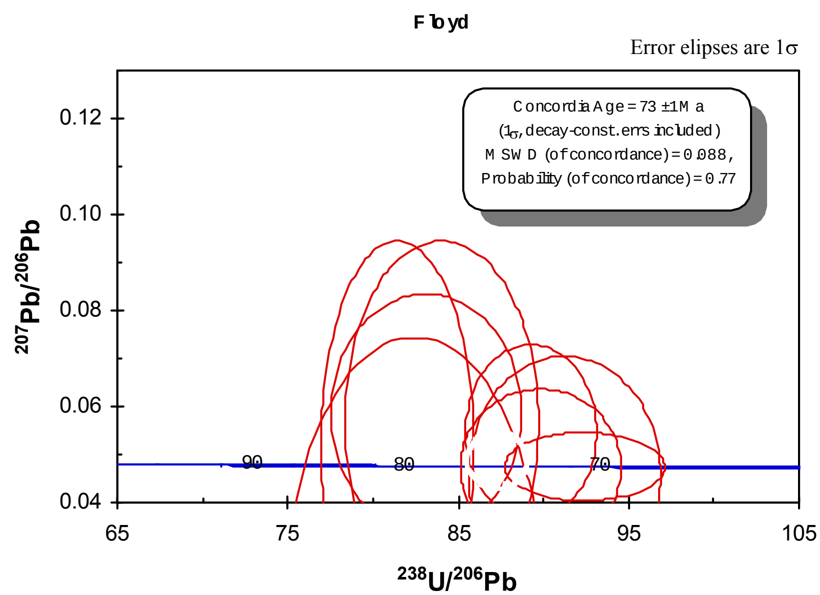
Figures 3 and 4. Tera-Wasserburg Concordia plots for Calvin and Floyd. Red circles are 1σ errors and blue circle represents the weighted mean Concordia age. Inherited cores were not used in the calculation of the ages. Figures 3-10 were created using Isoplot/Ex rev. 2.49 created by Kenneth R. Ludwig.



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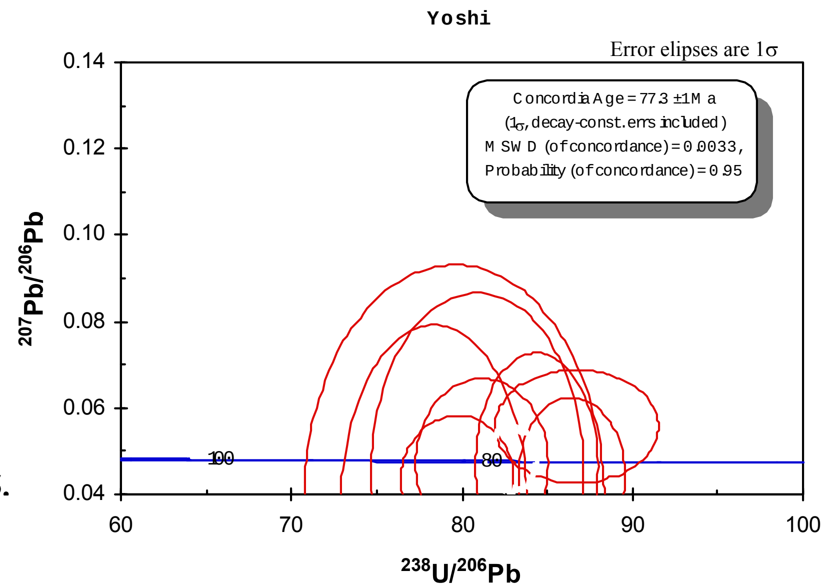

Figures 5 and 6. Tera- Wasserburg Concordia diagrams for Yoshi and Omar. Red circles represent 1σ errors with the blue circle representing weighted mean Concordia age. Age calculation did not include older inherited cores.

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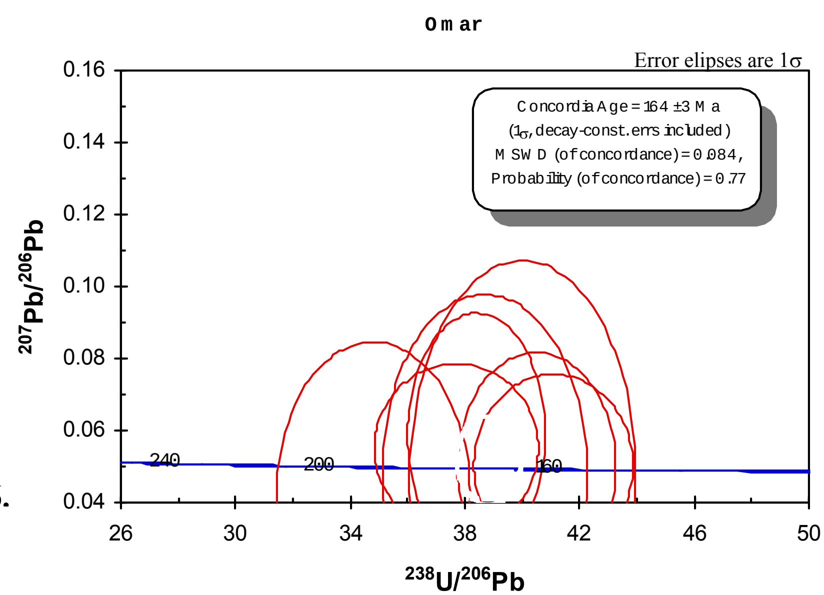

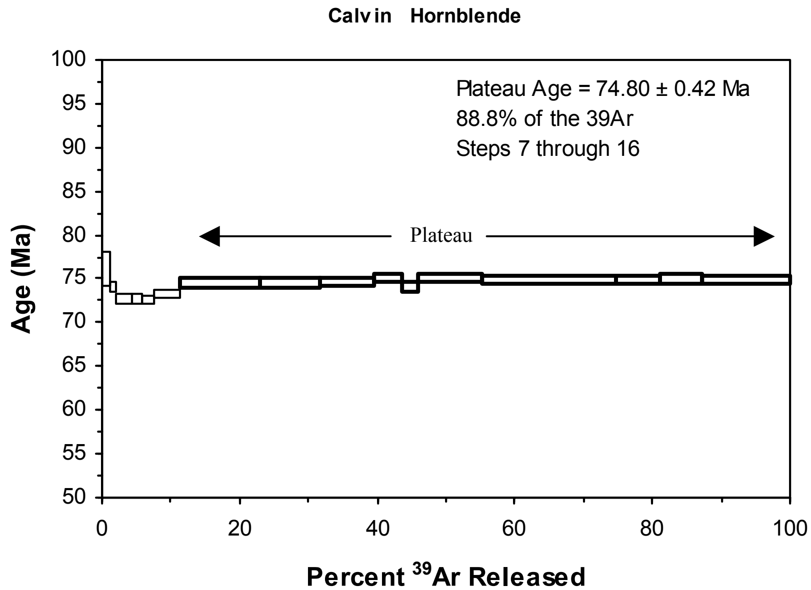

Figure 7. $^{40}Ar/^{39}Ar$ age spectrum for Calvin with a 88.8% of the ^{39}Ar released yielding a plateau age of 74.8 ± 0.4 Ma.

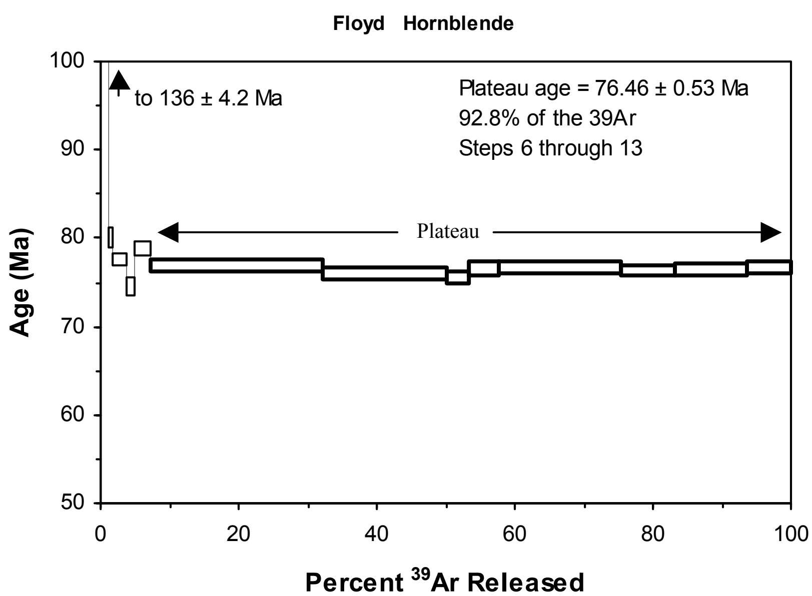

Figure 8. $^{40}Ar/^{39}Ar$ age spectrum for Floyd. Plateau age of 76.5 ± 0.5 Ma was calculated using 92.8% of the ^{39}Ar released.

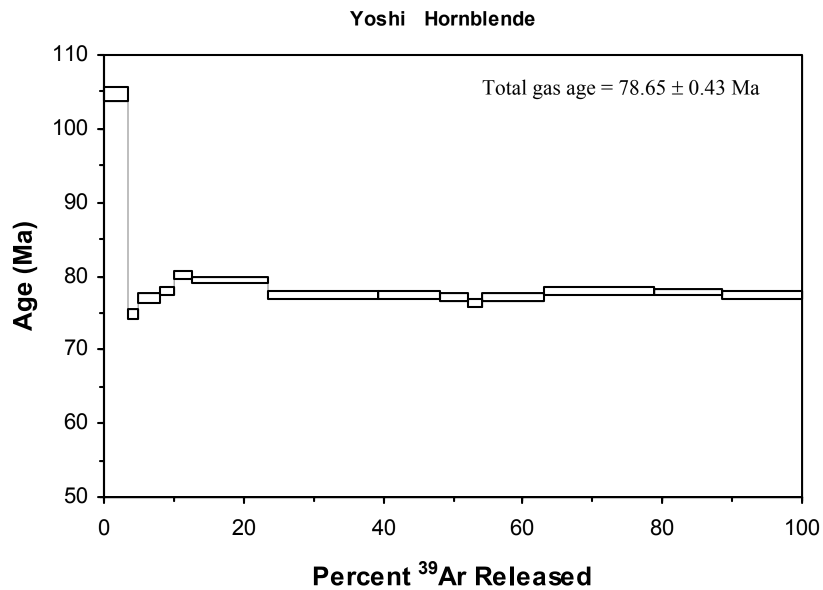

Figure 9. $^{40}Ar/^{39}Ar$ age spectrum for Yoshi. There was no plateau age, but the flat spectrum and agreement with U/Pb zircon age gives confidence in the total gas age of 78.65 ± 0.43 Ma.

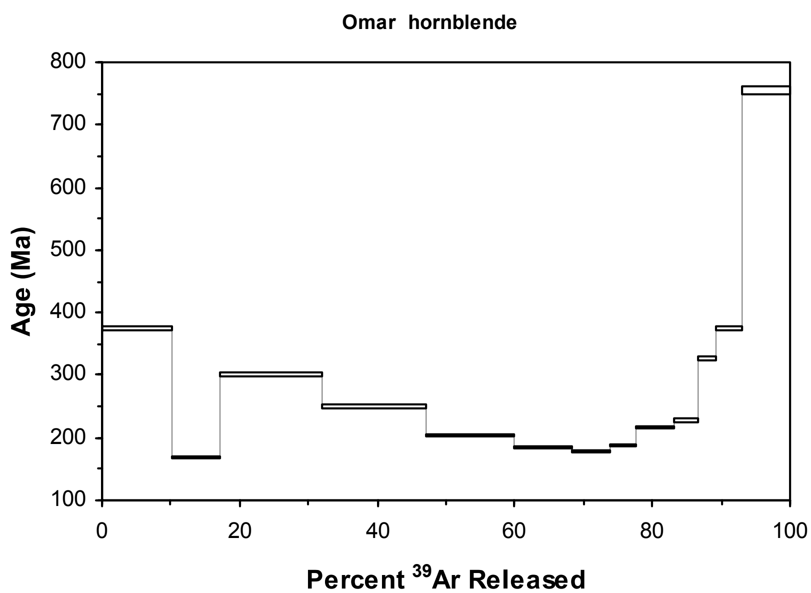

Figure 10. $^{40}Ar/^{39}Ar$ age spectrum for Omar. Discordant, 'U'-shaped spectrum is common for samples with excess argon. The total gas age of 286.2 ± 1.4 Ma is much higher than the U/Pb zircon age determined, 164 Ma, so the $^{40}Ar/^{39}Ar$ age is considered erroneous due to excess argon. For age spectra such as this, the minimum age on the spectrum (168 Ma) must be considered a maximum age for the sample.