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Analytical Data to Accompany "Eocene Igneous Geology and Relation to Mineralization: Railroad District, Southern Carlin Trend, Nevada" in *Geological Society of Nevada Symposium Proceedings, May 18–21, 2015*

by

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APPENDIX 1: Geochronologic Methods and Results

Analyses for this study were done by the $^{40}Ar/^{39}Ar$ method at the New Mexico Geochronology Research Laboratory, New Mexico Bureau of Geology and Mineral Resources (McIntosh et al., 2003; http://geoinfo.nmt.edu/labs/argon/home.html) and by U-Pb at the Jackson School of Geosciences, The University of Texas at Austin (LA/ICP-MS; Laser-ablation Inductively Coupled Plasma-Mass Spectrometry; http://www.jsg.utexas.edu/he-lab/u-thhe-and-upb-hr-icp-ms-lab/) and the Stanford/USGS SHRIMP (Sensitive High-Resolution Ion MicroProbe; http://shrimprg.stanford.edu/).

Mineral Separation

Samples were crushed, ground, and sieved to appropriate mesh sizes (between ~20 and 100 mesh for different minerals). Minerals were concentrated with a Frantz magnetic separator and various heavy liquids, then handpicked under a binocular microscope. In addition, sanidine, K feldspar, and plagioclase were leached with 5% HF for ~1 hour to remove adhering matrix and alteration material. Zircon for U–Pb geochronology was concentrated with a Gemini table (essentially a density panning method) and methylene iodide (density ~3.3), then handpicked under a binocular microscope. Final separates were as close to 100% pure as could be determined with a binocular microscope. However, most of these minerals contain mineral and/or fluid inclusions, so final separates are rarely 100% pure.

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

$^{40}Ar/^{39}Ar$ mass spectrometry measures 5 Ar isotopes: (1) ^{40}Ar, which is mostly a combination of radioactive decay of ^{40}K (used to calculate an age) and from atmosphere (which is approximately 1% Ar). (2) ^{39}Ar, which is produced from ^{39}K by irradiation with neutrons in a nuclear reactor, is a measure of the K content of a sample, and is used with radiogenic ^{40}Ar to determine the age of each analysis. (3 and 4) ^{38}Ar and ^{37}Ar, which are used to correct for interfering isotopes. (5) ^{36}Ar, which is a measure of the amount of atmospheric Ar in each analysis. The $^{40}Ar/^{36}Ar$ ratio of atmospheric Ar is 295.5, so the measured ^{36}Ar is multiplied by 295.5 to calculate the amount of ^{40}Ar from air in the analysis. That "atmospheric" ^{40}Ar is subtracted from the total analyzed ^{40}Ar to get the radiogenic ^{40}Ar.

Sanidine and plagioclase phenocryst separates were analyzed by the single crystal method, using a CO_2 laser to fuse individual grains. This method produces groups of 10 to 20 individual age determinations for each sample. A weighted mean age of a sample is calculated from all good analyses, after discarding analyses of obvious xenocrysts or altered grains. Plagioclase, K feldspar, adularia, biotite, hornblende, and muscovite or sericite were step-heated by progressively increasing the power in a resistance furnace or with the CO2 laser. This method produces a series of 8 to 15 individual ages, one at each temperature increment. Step-heating allows calculating three separate ages: (1) a plateau where contiguous individual steps accounting for more than

50% of the released Ar agree within analytical uncertainty. This method assumes that any non-radiogenic Ar has the $^{40}Ar/^{36}Ar$ ratio of atmosphere, 295.5. (2) An isochron using the same analyses but plotted and calculated without the assumption that any non-radiogenic Ar has an atmospheric composition. This method allows determining the presence of any "excess" Ar, which is Ar trapped in a mineral when it crystallized that does not have the $^{40}Ar/^{36}Ar$ ratio of atmosphere. Samples in which plateau and isochron ages agree do not have excess Ar. Hornblende from sample H12-110 of granodiorite does have excess Ar (see main text and table AgeRailroad). (3) A total gas age is calculated from all analytical steps and is similar to a conventional K-Ar age. Total gas ages are mostly not used to estimate the true age of a rock but are similar to plateau and isochron ages in samples that have had simple geologic histories.

Zircon U-Pb Analyses

Selected zircon grains were mounted on glass slides and cast in 25 mm diameter epoxy disks with the laboratory standard R33. Grainmounts were washed with a saturated EDTA solution, rinsed in distilled water, dried in a vacuum oven, and polished with diamond compound to expose the mid-points of the crystals. Polished grain mounts were imaged in reflected light with an optical microscope, gold-coated, and imaged in cathodoluminescence (CL) mode with a JEOL 5600 scanning electron microscope. Figure CL shows selected CL images of zircons showing analyzed spots and ages. The imaging shows that zircons are almost all complexly zoned, with oscillatory zones similar to those in plagioclase, sector zones, cores commonly of zircon xenocrysts, and particularly complex irregular zones, and contain inclusions of other minerals, most commonly apatite. Using beam analysis such as with the SHRIMP or LA/ICP-MS allows analysis of only small parts of each zircon to avoid mixing of ages with older cores, zones that grew at analytically distinct times in the zircons history, or analysis of inclusions.

Zircon U-Pb geochronology was carried out with the USGS-Stanford SHRIMP-RG (sensitive high-resolution ion microprobe-reverse geometry) ion microprobe at Stanford University. The SHRIMP-RG was operated with an O_2^- primary ion beam at ~6 nA, which produced a spot with a diameter of ~26 by 30 μm and a depth of 1–2 μm on the target zircons. The beam was rastered for 140 seconds over the area to be analyzed before data were collected. Twenty-one peaks (plus background) were measured sequentially five times each (mass in parentheses): Y(89), La(139), Ce(140), Nd(146), Sm(147), Eu(153), Gd(155), DyO(179), ErO(182), YbO(188), Zr_2O(196), HfO, ^{204}Pb(204), ^{206}Pb(206), ^{207}Pb(207), ^{208}Pb(208), ^{232}Th(232), ^{238}U(238) ThO(248), UO(254), UO_2(270). Concentrations were calibrated against in-house standard MAD-green zircon from Madagascar; ages were calculated by calibration against zircon standard R33 (419 Ma, quartz diorite of Braintree complex, Vermont, Black et al., 2004) which were analyzed repeatedly throughout the duration of the analytical sessions. Data reduction followed the methods described by Williams (1997) and Ireland and Williams (2003), and used the Squid and Isoplot programs of Ludwig (2001, 2003).

Preparation of zircon for analysis by LA/ICP-MS is similar to that by SHRIMP, but the lab at The University of Texas at Austin has not yet published a complete analytical method. The laser ablation beam drills a substantially deeper hole in the zircon, in fact can drill entirely through a grain. Age analysis is done continuously as the laser drills through the grain, so consistency or variation in age can be measured through the grain. This allows assessing whether growth zones developed during measurably different times and if distinctly older cores are present.

Explanation of U-Pb Results

Full analytical results are in Excel files A1UPb_UT and A2UPb_Shrimp. These files are generated in a version of Excel that has an added macro IsoPlot for calculating isotopic ages. Opening the files in Excel without IsoPlot should not be a problem, but if a question about "updating" pops up, always check the don't update box. Individual spreadsheets in these files have the basic data and various plots of the data. Probability density plots simply take the 206/238 age and plot as a histogram. In the most straightforward samples, a probability density peak is commonly the best age estimate; see H12-110 in UPb_UT for a good example. TuffZirc is an age calculation from IsoPlot that selects a coherent set of analyses with consistent ages; again see H12-110 in UPb_UT for a good example (38.27+0.16/-0.22 Ma). Concordia and Tera-Wasserburg plots are both "concordia" plots where the $^{206}Pb/^{238}U$ age is plotted against the $^{207}Pb/^{235}U$ age (standard concordia) or the $^{206}Pb/^{207}Pb$ age (TW). TW plots are preferred for relatively young, e.g., Cenozoic ages. See H12-110 in UPb_Shrimp for an example TW plot. Analyses for which the analytical ellipse overlaps with the "concordia" curve are concordant; analyses where the ellipse does not overlap with the curve are discordant and generally not used in an age calculation. Note that all the analyses of H12-110 zircon in UPb_Shrimp are concordant and spread from ~40 to 37 Ma. The TuffZirc age is 38.91+0.27/-0.90 Ma, which overlaps with but has an older absolute value than the TuffZirc age determined at Texas. An average of the Shrimp ages is 38.6±0.3 Ma, which shows a better apparent agreement with the Texas data.

University of Texas at Austin LA/ICP-MS results

H12-110. Granodiorite initially interpreted to be Cretaceous based on Gillerman dissertation, but it is definitely ~38.2 Ma. H12-110 is the freshest sample of this rock type, from outcrop at 40.527768, -116.014905 (NAD27) and has most straightforward results. 33 analyses of 29 zircons.

TuffZirc = 38.27 +0.16/-0.22 Ma (20 analyses)

Average of 16 concordant analyses = 38.22±0.18 Ma.

Concordia and TeraWasserburg plots have intercepts at 38.11±0.16 and 38.12±0.16 Ma, respectively

Probability Density shows dominant age peak at ~38.2 Ma.

The four ages at ~42 Ma are probably inherited zircons from an intrusion of that age.

RR12-10-400'. Hydrothermally altered, unoxidized dacite sill above mineralized zone, no quartz phenocrysts. Collar at 584879E, 4488764N. 23 analyses of 20 zircons.

TuffZirc = 38.40 +0.63/-0.55 Ma.

Concordia and TW plots have age clusters at 38.X Ma.

Probability Density shows dominant age peak at 38.45 Ma.

Very good correlation between zircon U content and age (figure A1); high U zircons have younger apparent ages, indicating Pb loss from radiation damage.

RR12-05-746'. Hydrothermally altered, unoxidized dacite sill, no quartz phenocrysts. Collar at 585062E, 4488727N. Only 10 analyses from 9 zircons.

TuffZirc = 38.22 +0.44/-0.20 Ma (from 6 analyses but very good agreement with RR12-10-400 and H12-110.

Probability Density shows dominant age peak at 38.45 Ma.

Concordia plot shows the cluster of concordant ages at ~38.5 Ma.

The 6 zircons giving 38.22 Ma all have moderate to low U contents.

H12-142. Very altered, oxidized, sparsely quartz-phyric dacite dike or sill in Pod deposit at 40.53388, -116.005245; very bleached so looks like a rhyolite. 32 analyses of 28 zircons.

Continuum of ages from ~39 to 35 Ma (See e.g., H12-142ConcordiaAll and the Probability Density plot, which has peaks at ~38.7, 37.4, and 35.9 Ma). TuffZirc of all ages = 37.47 +0.36/-0.27 Ma. TuffZirc of a subset is 38.55 +0.37/-0.41 Ma.

This is probably ~38.5 Ma and similar in age to the dacites from RR12-10 and RR12-05, in which case the younger ages indicate Pb loss. The plot of U content of zircon versus age shows that age decreases with increasing U content (figure A1). An alternative that the rock is ~37.5 Ma and the older zircons are inherited from older rocks is less likely.

H12-154. Altered but unoxidized porphyritic dacite – low-Si rhyolite with plagioclase, quartz, biotite, and hornblende phenocrysts, from the west-northwest "Standing Elk" trend at 40.52374, -116.022426. 23 analyses of 22 zircons.

Continuum of ages from ~39 to 35 Ma but concentration at ~36.8 Ma (See Concordia and Probability Density plots. Probability Density plot has a main peak at 36.85 Ma, with a lesser peak at 38.45). TuffZirc of all ages = 36.75 +0.14/-0.48 Ma, reflecting the main Probability Density peak. Similar to H121-142, this could be 38.45 Ma, with younger ages indicating Pb loss, or a younger intrusion with inherited zircons. Increasing U content correlates with decreasing age, similar to H12-142, and with two, young, very U-rich flyers. This pattern suggests that the young ages are from Pb loss. This is probably ~38.4 Ma, but it is the least conclusive determination.

Stanford-USGS SHRIMP U-Pb results

H12-110. Granodiorite, repeated for comparison to UT data. 16 analyses of 16 zircons, all rims, which are presumably the part that crystallized last, just before or during final intrusion and cooling-solidification of the magma.

TuffZirc of all ages = 38.91 +0.38/-0.90 Ma.

Average of 13 concordant analyses = 38.6±0.3 Ma.

TeraWasserburg plot shows concordant ages between ~37 and 40 Ma.

Probability Density shows two age peaks at ~37.6 and 39.2 Ma.

RRB12-03 526. Granodiorite from drillhole. Most straightforward of the new data. 16 analyses of 16 zircons, all rims.

TuffZirc = 38.21 +0.43/-0.22 Ma.
Average of 15 concordant analyses = 38.2±0.2 Ma.
TeraWasserburg plot shows cluster of concordant ages ~38.2 Ma.
Probability Density shows dominant age peak at ~38.2 Ma.

RR11-09 1225. Altered dacite dike. 22 analyses of 21 zircons, all rims.

TuffZirc of all ages = 37.55 +0.47/-0.71 Ma. TuffZirc of a subset = 38.77 +1.22/-0.85.
Average of 13 concordant analyses = 38.9±0.4 Ma.
TeraWasserburg plot shows concordant ages between ~36 and 40 Ma.
Probability Density shows two age peaks at ~37.1 and 39.1 Ma.
1 Jurassic (~154 Ma) and 1 Proterozoic or Archean ($^{207}Pb/^{206}Pb$ = 2613 Ma)

RR12-05 1425. Altered dacite dike. Only analyses of 6 zircons, but the ages are very tight and consistent with ages of other dacite dikes.

TuffZirc = 38.28 +0.64/-0.20 Ma.
Average of 6 analyses = 38.4±0.4 Ma.

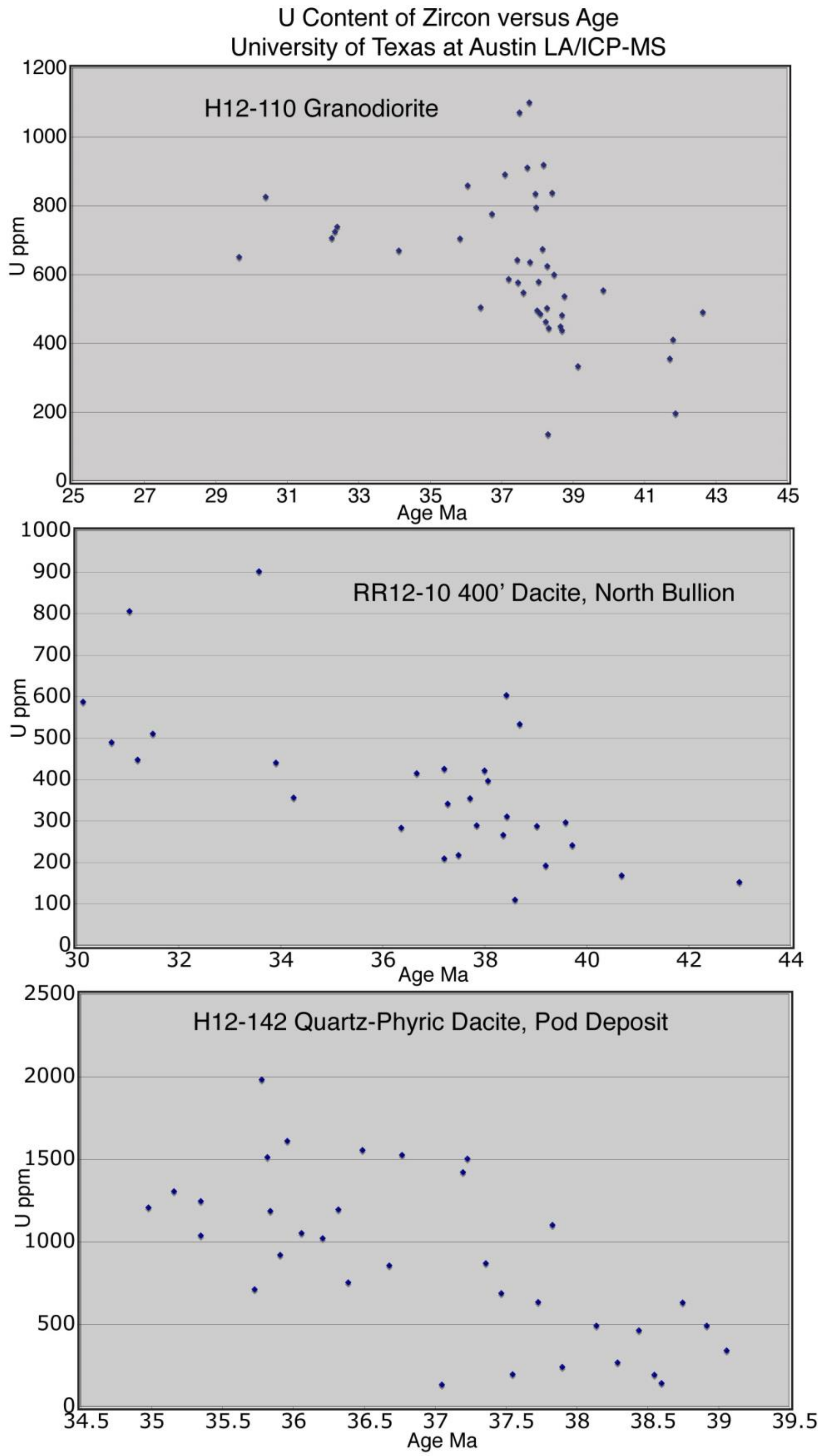

Figure A1. Plot of U content of zircon versus age for three representative samples.

Interpretation of $^{40}Ar/^{39}Ar$ Analyses

Full analytical results are in Excel files A3SingleCrystalx, A4StepHeatx, and A5KsparStepx with data plots in their individual spreadsheets. Analyses of unaltered, glassy clear sanidine phenocrysts are the most simple and straightforward to interpret. The best age estimate is the mean of all good analyses, weighted by the uncertainty of the individual analysis. For many samples, all analyses are "good". Analyses that are discarded include those (1) of plagioclase that slipped through mineral separation (as indicated by K/Ca ratios less than 1, (2) with low radiogenice Ar contents (almost all sanidine analyses are ≥99% radiogenic), (3) with ages significantly older than the mean (probably xenocrysts; significantly generally means more than 2 standard deviations from the mean), and (4) ages significantly younger than the mean (commonly altered grains, which also can have lower radiogenic Ar and different K/Ca).

Sample H12-87 of the porphyritic rhyolite (quartz porphyry intrusion or lava dome) east of the Bullion fault is a good example of a simple sanidine analysis (figure A2). All 12 analyzed grains make a single population with high radiogenic yields (all except 1 ≥99.9%) and consistent high K/Ca. The weighted mean age of 37.781±0.016 Ma is the best estimate of its time of emplacement. Removal of analysis 01 of that sample, which is only 97.0% radiogenic, has a slightly low K/Ca, and has the oldest calculated age, reduces the mean age to 37.775±0.015, a difference of only 0.006 Ma.

Analyses of sanidine that have undergone significant alteration or of Kspar phenocrysts are not as simple or precise. Kspar is distinguished from sanidine in being slightly turbid, which can be seen both in hand specimen and thin section by a general cloudiness of the phenocrysts. The phenocrysts retain a highly reflective cleavage surface but are translucent. Kspar grains also have Carlsbad twins and low negative 2V, similar to glassy sanidine, which suggests they are still the sanidine structural state. Origin of the turbid character is uncertain. Analyses of these grains show a much larger age scatter and lower radiogenic Ar contents than do those of glassy, unaltered sanidine. Sample H12-158 of a late rhyolite dike above the Standing Elk Mine is an example. Apparent ages of individual grains range from 37.28 to 37.91, and radiogenic yield ranges from 90.0 to 99.6%. The ages make three clusters, with 2 grains at ~37.3 Ma, 9 grains forming a broad cluster at 37.6 Ma, and two grains at 37.9 Ma. Because the 2 37.3 Ma grains also have the lowest radiogenic yields, they have been discarded. The weighted mean of the remaining 11 grains is 37.64±0.09 Ma.

$^{40}Ar/^{39}Ar$ dating of sanidine from five unaltered rhyolites from east of the Bullion fault illustrate the extreme precision of mass spectrometer analyses but also that geologic uncertainties are important (figure A2). Ages of three rhyolite ash-flow tuffs in stratigraphic order from oldest to youngest are: XT1 37.797±0.014 (H12-93), XT2 37.821±0.015 (H12-88), and XT3 37.834±0.015 (H12-94) (table 2). Obviously, the tuff dates do not match stratigraphy, although the total difference between them is <0.04 Ma and the plot of individual analyses shows that ages of all three samples overlap completely. This is because mass spectrometers can measure isotopes extremely precisely but cannot measure geologic uncertainty, e.g., geologic effects on the rocks over their 37 Ma lifetimes or mineral or melt inclusions that affect the ages.

Ideal step-heating analyses yield plateau, isochron, and total gas ages that agree. Ideal results arise from samples that have no excess Ar, cooled rapidly from magmatic or hydrothermal temperatures, and have not been altered or reheated subsequent to initial cooling. These conditions are only rarely attained in a long-lived igneous center with considerable hydrothermal activity such as Railroad.

Biotite from sample H12-105, a quartz-bearing dacite sill along the Roberts Mountains thrust near Webb Creek (figure 2), illustrates one of the simplest patterns where all three age calculations agree at ~38.5 Ma within uncertainties (file A4; table 2). The apparent age of the first step is ~36 Ma and may reflect slight alteration or reheating. Because this sill is at the outer edge of the center, it has probably been little affected by later igneous heating or alteration. As indicated by the similarity of the three age calculations, several other samples show approximately the same results (table 2).

Hornblende from sample H12-110, the fresh granodiorite, has excess Ar (file A4; table 2). An age of ~38.2 Ma is established for this sample by dating of biotite and zircon. In two separate analyses or hornblende, the first steps have apparent ages of 48 to 44 Ma, then drop to 41-42 Ma, and all apparent ages are older than the accepted age. The closest step to the accepted age is 38.49 Ma in the F step in the second analysis. Isochrons show that the sample has excess Ar but were unable to replicate the accepted age.

Step-heating of coarse K feldspar phenocrysts from coarsely porphyritic rhyolite samples H12-114 and H12-143 illustrate the effects of probable alteration and possible reheating (file A5). Initial steps for almost all runs have ages as old as 46 Ma. Subsequent steps drop to around 37 Ma, then climb slightly to ~38 Ma in the last steps. Four out of eight runs of sample H12-114 yielded apparent plateaus that range from 37.27±0.08 to 38.19±0.02 Ma. Obviously, not all of these can be a true age of crystallization. Calculated isochron ages show a similar large age range. Although these data demonstrate that the coarsely porphyritic rhyolites are broadly contemporaneous with the other rocks of the Railroad igneous center, it is not possible to determine precise ages.

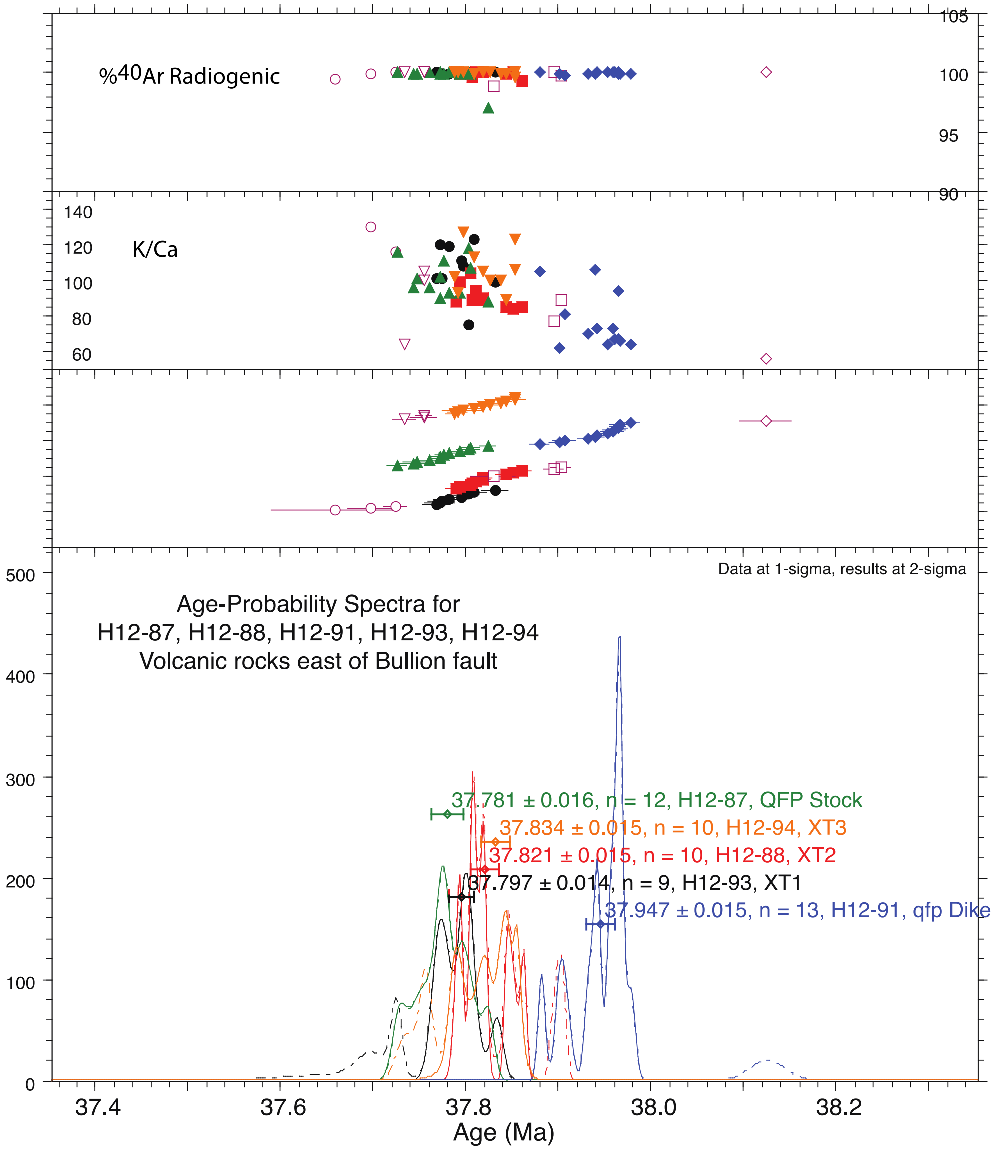

Figure A2. Age probability plots for sanidines from volcanic rocks east of the Bullion fault. Ages of XT1, XT2, and XT3 do not exactly match stratigraphy but vary by less than 0.04 Ma. This is because mass spectrometers can measure isotopes extremely precisely but cannot measure geologic uncertainty, e.g., geologic effects on the rocks over their 37 Ma lifetimes or mineral or melt inclusions that affect the ages.

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